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Analysis of Rotorwash Effects in Helicopter Mishaps

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EMA

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16. Abstract

A selected number of rotorwash related helicopter mishaps have been reviewed and analyzed. This analysis attempts to determine threshold levels of rotorwash velocity that result in potential hazards. Due to a lack of detailed mishap information being available, critical threshold values of velocity could not be conclusively identified. However, critical ranges of combined rotorwash and ambient wind velocity were identified for several types of investigated mishaps. These ranges of peak velocity generally occur between approximately 30 and 40 knots. Recommendations are provided for improvement of the rotorwash mishap reporting system and for the acquisition of experimentally obtained data which will significantly aid any future rotorwash related mishap analysis efforts.

A companion report, entitled "Evaluation of Rotorwash Characteristics for Tiltrotor and Tiltwing Aircraft in Hovering Flight," DOT/FAA/RD-90/16, evaluates rotorwash characteristics of 11 different types of tiltrotor and tiltwing aircraft for comparison purposes. Flight test data, as correlated with analysis tools, are presented for the XV-15 tiltrotor and CL-84 tiltwing.

A second companion report, entitled "Rotorwash Computer Model - User's Guide," DOT/FAA/RD-90/25, discusses the ROTWASH analysis program. This computer program is used to predict rotorwash characteristics of helicopter, tiltrotor, and tiltwing aircraft. The program also has the capability to analyze several different types of rotorwash related hazards which might be encountered in a vertiport environment.

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LIST OF ACRONYMS

AGL	Above ground level
DOT	Department of Transportation
FAA	Federal Aviation Administration
GW	Gross weight, pounds
NASA	National Aeronautics and Space Administration
PSF	Pounds per square foot
ROTWASH	Rotorwash Analysis Program
VTOL	Vertical takeoff and landing

1.0 INTRODUCTION

When rotorcraft are flown in confined areas or in close proximity to personnel and other aircraft, the potential exists for rotorwash-related mishaps. The prevention of these types of mishaps has historically been almost totally the responsibility of the rotorcraft pilot. In many instances, the pilot has been provided with only minimal help and guidance in execution of this task. Due to the design characteristics of some vertiports, heliports, helistops, and helipads, the prevention of mishaps can only be accomplished by restricting the size of user rotorcraft. With careful planning and design efforts, these types of limitations can generally be avoided. Unfortunately, planners and designers who have attempted to avoid restrictions have discovered that little guidance is available in the literature.

In response to these and other unrelated requests for guidance, the Federal Aviation Administration (FAA) has taken an aggressive role in recent years to work with the rotorcraft industry to improve all safety-related aspects of rotorcraft operation. An example of this effort is the development of the Heliport Design Advisory Circular (reference 1). Other documents have reviewed space requirements for surface maneuvering of helicopters (reference 2), rejected takeoff airspace requirements (reference 3), wind flow around buildings (reference 4), and visual flight rules heliport airspace requirements (references 5 and 6). Another recently published document (reference 7) presents a compilation and analysis of mishaps which have occurred at heliports and airports.

The analysis and prevention of rotorwash-related mishaps in close proximity to the ground was first investigated in reference 8. Proposed separation guidelines for the safe operation of rotorcraft at heliports and airports were also presented in the document. These guidelines were based upon an analysis of documented mishaps from numerous sources and the best available analytical tools at that time. Recommendations for future work to improve the proposed separation guidelines were included. Rotorwash characteristics for 11 different types of tiltrotor and tiltwing aircraft in hover are documented in reference 9. These rotorwash characteristics were developed using an improved mathematical model that predicts rotorwash characteristics for both single main rotor and twin rotor configurations (reference 10). The initial version of this mathematical model was developed and documented in reference 8. The tiltrotor and tiltwing rotorwash characteristics are documented for use in designing vertiports to avoid rotorwash-related mishaps. These types of rotorcraft possess rotor disk loadings which are higher than those of conventional helicopters. Extensive correlation of flight

test data with predicted rotorwash characteristics is documented in references 8 and 9 for Sikorsky CH-53E, Bell XV-15, and Canadair CL-84 aircraft.

The rotorwash-related mishaps analyzed in this report are intended to further expand the work initiated in references 7 and 8. More specifically, the goals are to:

1. define thresholds that, when exceeded, increase the probability that mishaps will occur,

2. document recently discovered and reviewed mishap data for future use by all segments of the rotorcraft community,

3. review and improve analysis methodologies first developed in reference 8 and develop new analysis approaches as required (when feasible), and

4. provide recommendations for further research.

The objectives of this report are accomplished through use of the analysis procedure and analytical tools described in the next section.

2.0 ANALYSIS APPROACH

The development of a methodology for the classification and analysis of rotorwash-related mishaps is primarily a three-part process. This process involves:

1. identification of important types of mishaps,

2. mathematical modeling of the mishaps, and

3. evaluation of the analyzed mishaps to determine critical threshold values of rotorwash velocities.

A block diagram of the analysis methodology used in this report is presented in figure 1. The completion of each task provides information needed to develop recommended safe separation guidelines. Separation guidelines could be developed between rotorcraft and ground personnel, ground vehicles, other rotorcraft or fixed-wing aircraft, ground structures, and equipment frequently found in the rotorcraft operational environment. As noted by a review of the report goals, it is not a goal of this report to define rotorcraft separation guidelines. Instead, the goal is to develop background data to support the future development of separation guidelines that may be required.

The first task in the three-part process involved the identification of rotorwash-related mishaps for analysis. In this study, a mishap is defined as the occurrence of an undesirable event which is believed to have been initiated by rotorwash. The amount of damage incurred may vary from minimal to complete destruction. Sources for the identified mishaps included the military services, government agencies, and rotorcraft operators. Each mishap proposed for the final list of mishaps was reviewed beforehand to ensure that an analysis of the mishap would contribute toward project goals. Unique or spectacular mishaps not likely to occur again in the future were eliminated from consideration. Similiar mishaps from the mishap data base documented in reference 8 were added to the list. The merging of the newly discovered mishap information with the previously reviewed data from reference 8 helped to develop an improved perspective on how mishaps occur.

The mathematical modeling task provides the tools to understand the physics of mishaps and eventually to evaluate separation guidelines. As shown by the feedback loop in figure 1, the modeling task is iterative and therefore an inexact task. The modeling of mishaps in the future will continue to be an iterative task, because a large number of scenarios exist for most common types of mishaps. By nature, mishaps are also not controlled experiments.

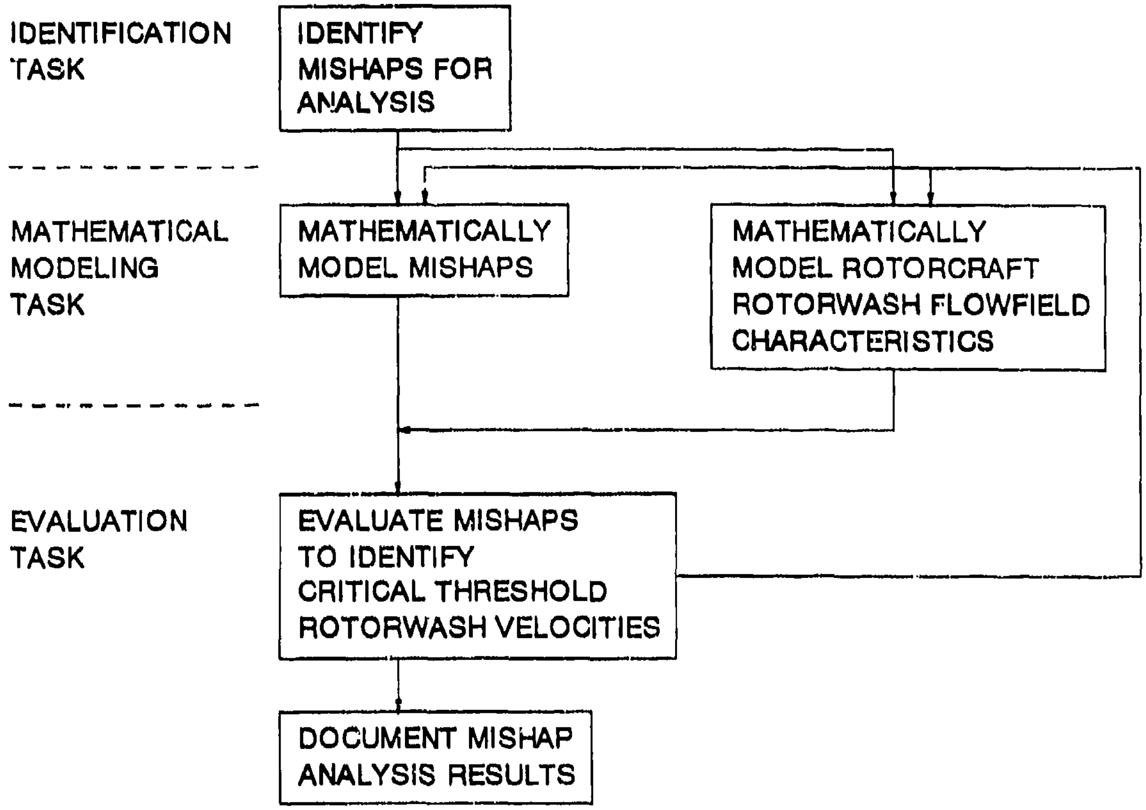

FIGURE 1 ANALYSIS METHODOLOGY FLOW CHART

Therefore, detailed documentation of parameters such as wind, aircraft gross weight, mishap geometry, etc., is rarely available. If information of this type is provided, it is almost always someone's best recollection of events at a much later point in time. Most of the mishaps discussed in this report had to be studied iteratively several times. Therefore, results presented from this type of analysis must be qualified as an investigator's "best estimations" of conditions occurring at the time of the accident. Results can never be presented as facts. This weakness in the analysis approach makes it imperative that as many mishaps as possible be studied. Hopefully, a statistical significance can then become the basis for any reported results when separation guidelines are eventually proposed.

The mathematical models used in this effort were developed specifically for the mishaps being studied, or were obtained or modified from those presented in reference 8. All helicopter rotorwash velocities estimated in the

analysis effort were calculated using the improved rotorwash analysis computer program (ROTWASH). The initial version of this program was developed in 1986. A detailed description of the mathematical model is documented in reference 8. The improved version was developed in 1989 and is available for use on IBM-PC compatible computers. The user's guide and mathematical model improvements are documented in reference 10. Validation of this mathematical model with flight test data from the Sikorsky CH-53E, Bell XV-15, and Canadair CL-84 (references 11, 12, and 13 respectively) is contained in references 8 and 9. This correlation provides increased confidence in the quality of the estimated rotorwash characteristics for the numerous helicopter configurations analyzed in this report. Limited flight test data were also obtained from references 14 and 15 to aid in the analysis of several mishaps.

The goal of the evaluation task in the three-part process was to attempt to determine if critical threshold values of rotorwash velocity could be identified. This goal was accomplished for some of the types of mishaps studied. These results should be useful as background for any future development of separation guidelines. The quantity and quality of available information for several other types of mishaps does not support any conclusions. In many instances, guidance for this task was provided through a review of work contained in reference 8. The final output of this task is the documentation contained in this report. Documentation presented in sections 3.0 and 4.0 includes discussion, analysis, and a statement of conclusions for the various types of studied mishaps, as well as recommendations for future work.

3.0 ANALYSIS OF ROTORWASH RELATED MISHAPS

All rotorwash-related mishaps studied for this report were initially sorted into one of six arbitrarily defined groups to simplify the analysis and reporting process. These six groups are the basis for the following sections that contain mishaps involving:

1. damage to parked rotorcraft,
2. overturning of light fixed-wing aircraft,
3. oil drums,
4. personnel injury,
5. damage to ground vehicles, and
6. damage to light structures.

The reader should understand that the group titles and the number of mishaps mentioned within each group have no statistical meaning. Numerous other types of rotorwash-related mishaps have been reported in the literature. Reference 8 contains a three page listing of the many types of rotorwash-related mishaps which have been reported. The statistical probabilities for the occurrence of any one specific type of rotorwash-related mishap can confidently be stated as unknown. No central clearinghouse exists for collection and reporting of these types of mishaps, because the offending rotorcraft rarely sustains damage and injuries to personnel are rarely life threatening. The military safety centers do the best job of collecting data; however, even their efforts rarely provide enough detailed information for subsequent mishap analysis efforts. This is partially due to the lower priority assigned to the investigation of these types of mishaps.

3.1 DAMAGE TO PARKED ROTORCRAFT

Damage inflicted on parked rotorcraft by other hovering or taxiing rotorcraft can be as minor as scratched paint; it can also result in total destruction. Scenarios that have been associated with previously documented mishaps clearly indicate that a large percentage of future scenarios and associated damages will not be predictable. This is because most mishaps are unique and involve many complicating factors. However, several types of mishaps do occur with sufficient regularity that limited analysis can be attempted. These types of mishaps involve damage to doors, cowlings, and rotor blades of parked rotorcraft. Damage to one of these aircraft components often results in secondary

damage to such components as windshields and chin bubbles. Any subsequent reduction in the probability of occurrence for these types of mishaps will also help to minimize the occurrence of many of the more unique mishaps reported in the literature.

The number of mishaps investigated involving damage to doors and cowlings totaled 28. Nine different types of helicopters were represented by this group, the smallest being the Bell 206 JetRanger, the largest being the Boeing CH-47, and the most numerous being the Bell UH-1. Of these 28 mishaps, 13 contained at least 1 quantitative fact which could be used in an analysis. The other 15 mishap summaries contained only qualitative information. None of the mishap reports provided details such as hover taxi speed, whether or not low speed maneuvering occurred during the mishap (i.e. cyclic flare), or gross weight for the rotorwash generating helicopters. This lack of information dictates that assumptions be made in the analysis effort. More will be said on this subject in the following sections. A representative example of one of the "quantitative" mishap summaries is presented below for informational purposes.

> "The landing UH-1H terminated a normal approach to a lighted helipad. While performing a post flight inspection on the parked helicopter, the crew chief left the pilot's door unlatched. The rotorwash from a landing helicopter opened the pilot's door with sufficient velocity to fracture the right door hinges, damage the doorpost mount, and shatter the right chin bubble. The parking area was less than 120 feet from the helipad. The parking area was relocated. The ground crew failed to follow unit operating procedures while completing duties during the post flight inspection."

This mishap summary provides an excellent example of a well-intentioned crew doing their job and making only one minor mistake, leaving a door unlatched just enough to be caught by rotorwash. Several reported mishaps involved people that were either entering or exiting the rotorcraft at the time the door or cowling damage was incurred. Fortunately, no injuries were reported to the crews or passengers involved in these mishaps. Damage resulting from an incident such as the one reported above can easily run into thousands of dollars.

3.1.1 Analysis Procedure

A "reverse engineering" analysis methodology was employed to investigate mishaps involving damage to other

rotorcraft. This type of analysis approach emphasizes the fact that mishaps occur and successful implementation of the approach depends on a set of assumptions being valid. These assumptions are:

1. rotorwash characteristics can be analytically estimated for documented mishaps,

2. if a large group of similiar mishaps are investigated, it is possible to identify common factors within the group, and

3. when common factors are identified, operational procedures can be developed to reduce the probability that further mishaps will occur.

It must be emphasized that the described analysis approach is not compatible with rigid scientific analysis procedures. Detailed rotorcraft, crew, ground personnel, and atmospheric related data obtained immediately prior to, during, and subsequent to most mishaps are rarely reported. One might more appropriately refer to the methodology as scientific guesstimation. Unfortunately, this type of methodology is probably the best tool that will be available in the foreseeable future for rotorwash mishap analysis.

The first step in the analysis methodology was to estimate rotorwash characteristics for offending rotorcraft. This task was accomplished using the ROTWASH analysis program (references 8 and 10). Rotorwash characteristics on the downwind side of the rotorcraft were calculated in hover for crosswind velocities of 0 and 9 knots at both the mid (one-half maximum payload) and maximum gross weights. All cases were computed at an atmospheric density ratio of 0.95. Wheel heights for the various rotorcraft varied from 25 feet for the small rotorcraft to 40 feet for the Boeing CH-47 (approximately one rotor diameter above the ground). Table 1 summarizes data values that were used in calculating Bell UH-1H rotorwash characteristics. This type of helicopter is used in several of the example cases presented in this report.

All calculated rotorwash data were subsequently plotted in a special format. An example of this format, using data for the UH-1H, is presented in figure 2. The radial distance from the center of the main rotor that generates the rotorwash (in feet) is plotted on the independent or x-axis. Calculated peak profile rotorwash velocity (in knots) is plotted on the dependent or y-axis. Data plotted in this format are derived from three positions along the rotorwash profile, as shown in figure 3. These positions are at 4 feet, 8 feet, and at the height above ground level along the

TABLE 1 UH-1H INPUT DATA FOR THE ROTWASH ANALYSIS PROGRAM

PARAMETER	VALUE	UNITS
Number of Main Rotors	1	-ND-
Main Rotor Separation	0.0	ft
Rotor Radius	24.0	ft
Gross Weight	7400.0, 9500.0	lb
Rotor Height Above Ground	30.0	ft
Rotor Download on Fuselage	2.0	%
Tilt of Rotor Tip Path Plane	0.0	deg
Atmospheric Density Ratio	0.95	-ND-
Wind Velocity	0.0, 9.0	kts

profile where the maximum peak velocity occurs (which increases in value as distance from the rotor increases). When plotted for both wind conditions and gross weights, these data form six bands of plotted results. The upper and lower range of values along each band are for the maximum and mid gross weight configurations respectively. Below the plotted data are several pictures of small UH-1H helicopters. These helicopters are positioned along the independent axis so that the rotor tips are spaced one-half of a rotor diameter apart when the rotor blades are indexed perpendicular to the fuselage centerline. These pictures provide visual information on spacing requirements when several helicopters operate in close proximity to one another. Position data derived from the mishap summaries are then marked along the independent axis at estimated positions where damage is reported to have occurred. While some mishaps may be marked at a specific location, the majority of mishaps are assumed to occur within some range, i.e., 100 to 120 feet, as shown for the hypothetical mishap #1 in figure 2.

The next step in the analysis methodolgy was to estimate a minimum safe distance from each type of offending rotorcraft after each mishap had been assigned an estimated

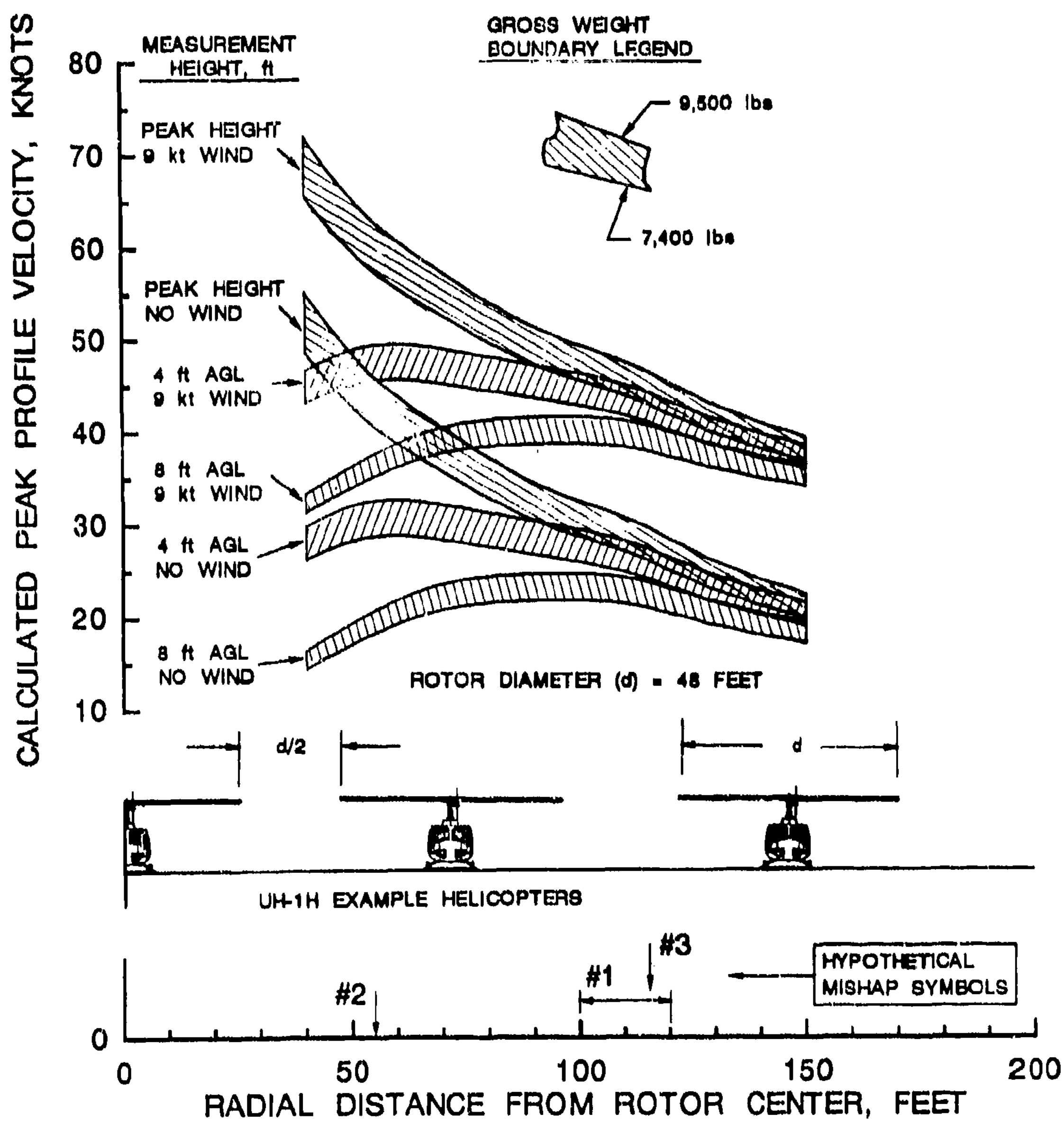

FIGURE 2 BELL UH-1H PREDICTION CHART FOR DOOR/ACCESS PANEL AND ROTOR BLADE/TAILBOOM STRIKE MISHAPS

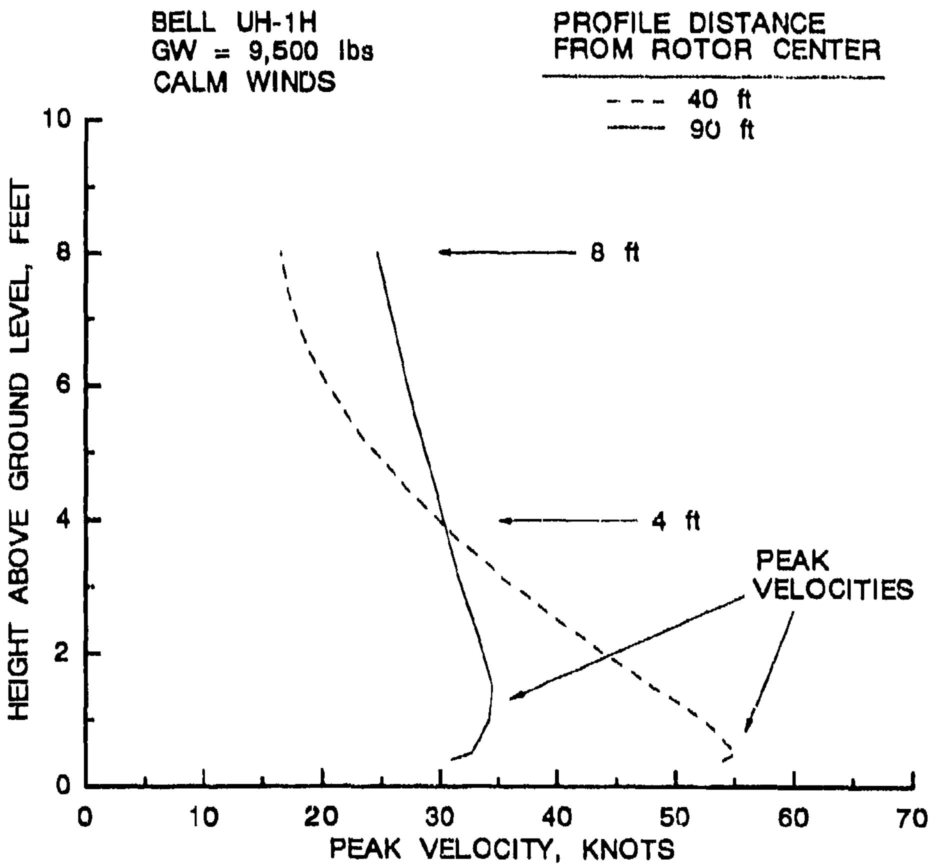

FIGURE 3 ROTORWASH VELOCITY PROFILE LOCATIONS PLOTTED IN THE DEVELOPMENT OF THE UH-1H ANALYSIS CHART PRESENTED AS FIGURE 2

location. At this position (or range of positions), the associated rotorwash velocities were estimated. In the example, hypothetical mishaps #1 and #3 occurred in calm air at an average position of approximately 110 feet. The estimated peak rotorwash velocity at this location at a door height (h_d < 4 feet) is between 28 and 31 knots. The final step in the analysis methodology combined the estimated rotorwash levels for each type of rotorcraft on one graph. At this point, the number of data points became sufficient to estimate the threshold value of rotorwash velocity that should be avoided. This subject is discussed in detail in the next section.

3.1.2 Analysis Results

The desired result from this mishap analysis was to identify a threshold value of peak rotorwash velocity. When this threshold velocity value is not exceeded in close proximity to unlatched rotorcraft doors and cowlings, the probability of a mishap should be significantly reduced. Estimated peak rotorwash velocity ranges, which should contain the threshold velocity value, are summarized in figure 4 for the nine types of rotorcraft investigated. The estimated velocities range in value from 19 to 69 knots, depending on the height above ground and on whether the ambient wind is 0 or 9 knots. Both wind speed ranges are considered because only 1 mishap summary (of a total of 28) documented an estimated ambient wind value. Therefore, the assumption is that the ambient wind is between these values. The choice of 9 knots as the upper limit is based upon an assumption, partially derived from work conducted in reference 8, that 9 knots may be close to the worst case scenario. Highly simplified sketches of the rotorwash flowfields for both 0 and 9 knot wind conditions are presented in Figure 5. Rotorwash flow fields formed in crosswinds exceeding 9 knots are believed to be less severe. This condition results because it is known that rotor aerodynamics at airspeeds in excess of 10 to 15 knots do not support the formation of the same types of rotorwash flow field structures as described in figure 5.

A second reason an ambient wind greater than 0 knots must be considered follows from the observation that the atmosphere is rarely calm (wind < 1 knot). Reference 16 notes that in the Cape Kennedv area, the atmospheric conditions at 10 meters are calm only 4.5 percent of the time; this condition often occurs during early morning hours. If the mean wind speed values for each of the locations listed in table 2 (reproduced from reference 17) are added together, an average wind speed of 8.5 knots can be computed for the United States. The probability that the windspeed is between 8 and 12 miles per hour is greatest at 68 percent of the locations. While not statistically representative for the rest of the world, the likelihood of calm atmospheric conditions at any specific location is relatively small.

The top bar for each range of velocity values presented in figure 4 represents the estimated maximum peak profile velocity for the maximum gross weight. This maximum peak velocity varies in height above the ground as a function of position with respect to the center of the rotor. The lower bar represents the peak velocity estimated for the mid gross weight at a constant 4 foot height above ground level. The 4 foot height is in close proximity to the height above ground of most rotorcraft doors. One generally accepted approach for merging the available data and estimating one

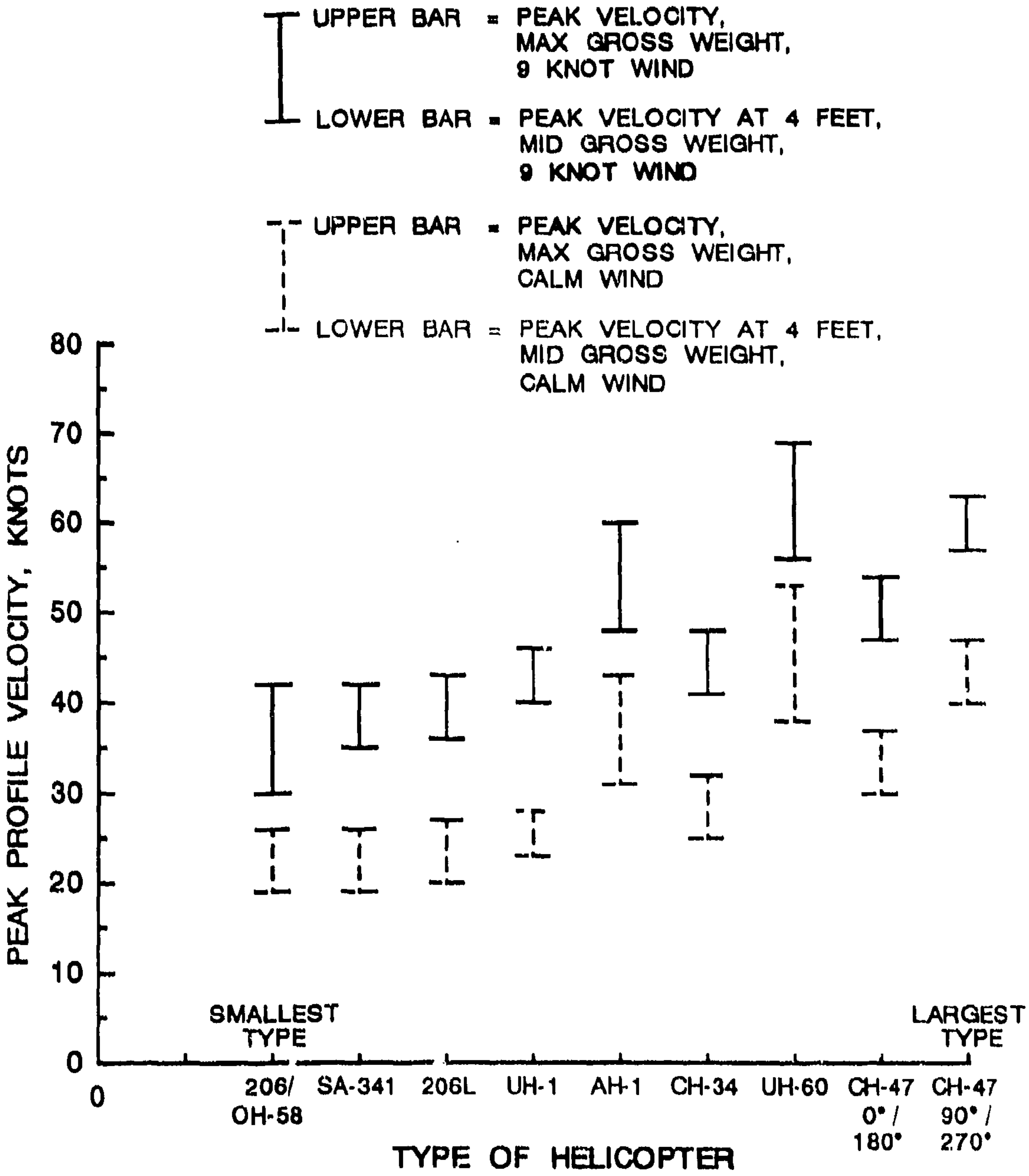

FIGURE 4 ESTIMATED THRESHOLD ROTORWASH VELOCITY RANGES FOR THE MISHAPS INVOLVING DOOR AND COWLING DAMAGE TO HELICOPTERS

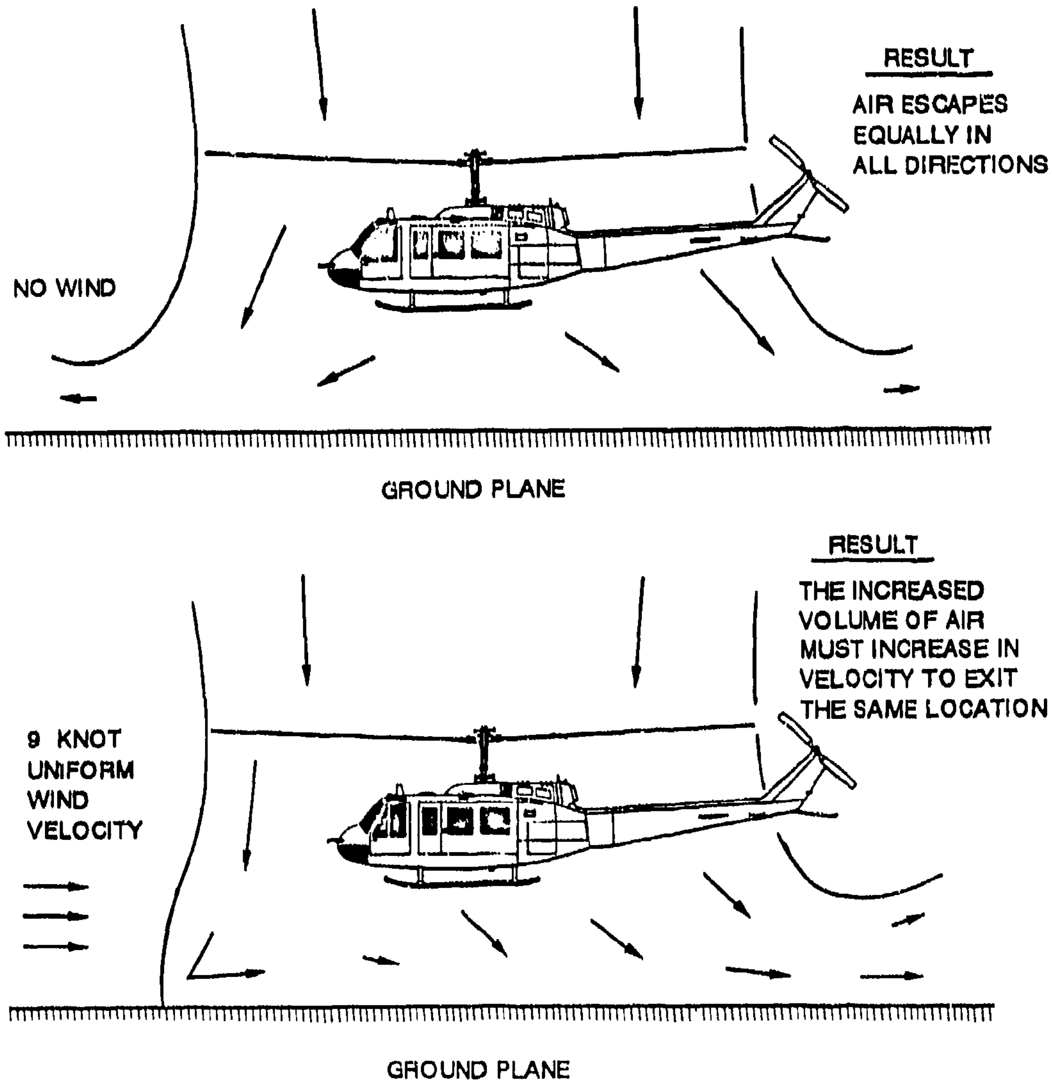

FIGURE 5 TYPICAL HOVER ROTORWASH FLOW PATTERN CHARACTERISTICS WITH AND WITHOUT WIND

TABLE 2 ANNUAL PERCENTAGE FREQUENCY OF WIND BY SPEED GROUPS AND THE MEAN WIND (Source: See reference 16)

STATE AND STATION	0 - 3 m.p.h.	4 - 7 m.p.h.	8 - 12 m.p.h.	13 - 18 m.p.h.	19 - 24 m.p.h.	25 - 31 m.p.h.	32 - 38 m.p.h.	39 - 46 m.p.h.	47 m.p.h. and over	Mean speed m.p.h.
ALA. Birmingham	27	22	30	17	3	1	*	*	*	7.9
Mobile	7	28	38	20	6	1	*	*	*	10.0
Montgomery	31	29	27	12	2	*	*			6.9
ALASKA, Anchorage	28	35	25	11	2	*	*	*		6.8
Cold Bay	4	9	18	27	21	14	5	2	*	17.4
Fairbanks	40	35	19	5	1	*	*	*		5.2
King Salmon	11	20	30	24	10	4	1	*	*	11.4
ARIZ. Phoenix	38	35	20	5	1	*	*	*		5.4
Tucson	18	35	30	14	3	1	*	*		8.1
ARK. Little Rock	12	30	39	16	2	*	*	*		8.7
CALIF. Bakersfield	35	30	24	10	1	*	*			5.8
Burbank	52	26	18	4	1	*	*	*		4.5
Fresno	30	41	22	7	1	*	*			6.1
Los Angeles	28	33	27	11	1	*	*			6.8
Oakland	29	28	26	16	2	1	*	*	*	7.5
Sacramento	13	28	31	18	5	1	*	*	*	9.3
San Diego	28	38	28	6	*	*	*			6.3
San Francisco	15	21	28	22	11	3	*	*	*	10.6
COLO. Colorado Springs	9	21	38	19	9	2	*	*	*	10.0
Denver	[illegible]	[illegible]	34	22	5	2	*	*	*	10.0
CONN. Hartford	13	25	32	24	6	[illegible]	*	*	*	9.6
D.C. Washington	11	26	35	22	[illegible]	1	*	*	*	9.7
DEL. Wilmington	15	31	30	19	4	1	*	*	*	8.8
FLA. Jacksonville	10	33	35	18	3	*	*	*		8.9
Miami	14	30	34	20	2	*	*	*	*	8.8
Orlando	16	28	32	17	4	*	*	*		8.6
Tallahassee	33	35	23	7	*	*				6.1
Tampa	3	31	43	18	2	*	*	*	*	8.8
West Palm Beach	8	22	38	27	8	1	*	*		10.5
GA. Atlanta	13	24	36	21	6	1	*	*		9.7
Augusta	[illegible]	28	25	9	1	*	*			6.3
Macon	10	26	45	16	2	*	*	*	*	8.9
Savannah	12	34	37	14	3	*	*	*	*	8.4
HAWAII Hilo	[illegible]	34	40	[illegible]	[illegible]	*	*			8.7
Honolulu	9	17	27	31	12	2	*	*	*	12.1
IDAHO Boise	15	30	32	[illegible]	4	1	*	*		8.9
ILL. Chicago O'Hare	[illegible]	22	33	27	8	[illegible]	[illegible]	*	*	11.2
Chicago (Midway)	7	26	36	25	5	1	*	*	*	10.2
Moline	14	25	32	24	7	2	*	*	*	10.0
Springfield	[illegible]	22	26	27	12	3	1	*	*	[illegible]
IND. Evansville	[illegible]	27	[illegible]	21	5	1	*	*		[illegible]
Fort Wayne	[illegible]	22	22	25	8	2	*	*	*	[illegible]
Indianapolis	[illegible]	22	34	26	7	2	*	*	*	[illegible]
South Bend	[illegible]	22	35	30	7	2	*	*		10.9
IOWA, Des Moines	[illegible]	17	39	29	10	3	1	*	*	12.1
Sioux City	10	20	32	25	10	4	1	*	*	11.7
KANS. Topeka	11	19	30	27	10	2	*	*	*	11.2
Wichita	4	12	30	31	16	5	1	*	*	13.7
KY. Lexington	8	25	39	22	6	1	*	*		10.1
Louisville	17	28	31	20	3	1	*	*		8.8
LA. Baton Rouge	17	29	34	17	3	*	*	*		8.3
Lake Charles	19	31	29	17	4	1	*	*	*	8.5
New Orleans	16	27	32	19	5	1	*	*	*	9.0
Shreveport	12	26	37	21	4	1	*	*	*	9.5
MAINE, Portland	10	30	33	22	4	1	*	*	*	9.6
MD. Baltimore	7	24	39	22	6	2	*	*	*	10.4
MASS. Boston	3	12	33	35	12	4	1	*	*	13.3
MICH. Detroit (City AP)	8	23	37	26	5	1	*	*	*	10.3
Flint	16	26	32	22	3	1	*	*	*	9.0
Grand Rapids	14	23	32	25	5	1	*	*	*	9.8
MINN. Duluth	6	15	33	31	11	4	1	*	*	12.6
Minneapolis	8	21	34	28	9	2	*	*	*	11.2
MISS. Jackson	33	25	26	14	2	*	*	*		7.1
MO. Kansas City	5	29	35	23	5	1	*			9.8
St. Louis	10	29	36	21	3	1	*	*	*	9.3
Springfield	4	13	34	32	13	3	1	*	*	12.9
MONT. Great Falls	7	19	24	24	15	9	3	1	*	13.9
NEBR. Omaha	12	17	29	23	11	3	*	*		11.6
NEV. Las Vegas	18	25	25	20	8	3	1	*	*	9.7
Reno	52	20	13	10	4	1	*	*	*	5.9
N. J. Newark	11	25	24	24	5	1	*	*	*	9.8
N. MEX. Albuquerque	17	36	26	13	5	2	*	*	*	8.6
N. Y. Albany	23	24	27	21	4	1	*	*		8.6
Binghamton	11	23	35	25	5	1	*	*	*	10.0
Buffalo	5	17	34	27	13	3	1	*	*	12.4
New York (Kennedy)	6	17	35	22	10	3	*	*	*	12.0
New York (La Guardia)	6	15	33	31	12	4	1	*	*	12.9
Rochester	8	22	34	25	9	2	1	*	*	11.2
Syracuse	14	27	30	23	5	1	*	*	*	9.7
N. C. Charlotte	20	22	31	14	2	*	*	*		7.9
Greensboro	[illegible]	[illegible]	31	14	2	*	*	*	*	8.0
Raleigh	18	30	34	14	2	*	*	*	*	7.7
Winston-Salem	19	[illegible]	33	21	4	1	*	*		9.0
N. DAK. Bismarck	14	[illegible]	27	24	12	3	1	*	*	11.2
Fargo	4	12	29	31	15	7	2	*	*	14.4
OHIO Akron-Canton	7	25	35	26	5	1	*	*	*	10.4
Cincinnati	11	27	36	22	4	1	*	*	*	9.8
Cleveland	7	18	35	29	9	3	*	*	*	11.6
Columbus	26	23	25	18	4	1	*	*	*	[illegible]
Dayton	8	25	36	23	6	1	*	*	*	11.3
Youngstown	[illegible]	25	36	24	6	1	*	*	*	[illegible]
OKLA. Oklahoma City	2	11	34	34	13	5	1	*	*	14.0
OKLA. (Cont.) Tulsa	9	24	34	26	7	1	*	*	*	10.6
OREG. Medford	47	31	14	6	2	*	*	*	*	4.6
Portland	28	27	25	16	4	1	*	*	*	7.7
Salem	25	32	28	13	2	*	*			7.1
PA. Harrisburg	28	31	25	13	3	1	*	*		7.3
Philadelphia	11	27	35	21	5	1	*	*	*	9.6
Pittsburgh	12	26	34	22	4	1	*	*		9.4
Scranton	11	33	35	18	2	*	*	*		8.8
R. I. Providence	11	20	32	28	7	2	*	*	*	10.7
S. C. Charleston	12	28	35	19	4	1	*	*		9.2
Columbia	23	35	26	12	2	*	*			7.0
S. DAK. Huron	10	18	29	29	10	3	1	*	*	11.9
Rapid City	15	22	28	21	10	4	1	*	*	11.0
TENN. Chattanooga	39	25	24	11	1	*	*			6.1
Knoxville	29	29	25	12	4	1	*	*	*	7.5
Memphis	14	26	34	20	5	1	*	*		9.4
Nashville	27	31	25	14	2	*	*	*	*	7.2
TEX. Amarillo	3	15	32	32	12	4	1	*	*	12.9
Austin	13	25	34	23	5	1	*	*		9.7
Brownsville	10	17	25	30	14	3	*	*	*	12.3
Corpus Christi	11	16	26	33	12	2	*	*		11.9
Dallas	9	21	32	28	9	1	*	*		11.0
El Paso	10	22	32	22	9	4	1	*	*	11.3
Ft. Worth	4	14	34	34	10	3	*	*	*	12.5
Galveston	4	10	35	33	16	2	1	*	*	12.5
Houston	6	16	36	28	10	2	*	*	*	11.8
Laredo	6	15	32	34	12	1	*	*		12.3
Lubbock	4	11	33	34	13	5	1	*	*	13.6
Midland	4	22	38	26	4	1	*	*		10.1
San Antonio	18	20	32	22	4	1	*	*		9.3
Waco	2	14	35	35	10	2	*	*		12.5
Wichita Falls	3	22	41	27	5	1	*	*	*	10.5
UTAH, Salt Lake City	12	26	36	14	4	1	*	*	*	8.7
VT. Burlington	24	34	28	22	2	*	*			8.3
VA. Norfolk	14	22	30	25	8	1	*	*	*	10.2
Richmond	14	27	36	11	1	*	*	*		7.8
Roanoke	31	22	22	17	5	2	*	*		8.3
WASH. Seattle-Tacoma AP	13	18	35	26	5	2	*	*	*	[illegible]
Spokane	17	33	27	14	3	1	*	*		8.1
W. VA. Charleston	39	[illegible]	25	8	1	*	*			6.2
WIS. Green Bay	5	22	33	26	10	2	*	*	*	11.2
Madison	15	22	30	23	7	2	*	*	*	10.1
Milwaukee	8	17	31	30	11	3	1	*	*	12.1
WYO. Casper	9	15	27	27	13	7	2	*	*	13.3
PACIFIC Wake Island	[illegible]	[illegible]	27	48	17	2	*	*		14.6
P. R. San Juan	15	26	27	25	4	*	*	*	*	9.1

Source: Climatography of the United States Series 82; Decennial Census of the United States Climate -- Summary of Hourly Observations, 1951-60 (Table B)

meaningful threshold value of rotorwash velocity is to use statistical methods. However, a question quickly arises on how the data should be defined for use in statistical calculations. This issue is further compounded when each of the assumptions used to derive these data are reviewed. As a result, it becomes obvious that rigorous scientific analysis methods can not be used and subsequently defended with a high level of confidence.

The alternative analysis approach is to define a velocity range containing the unknown threshold value of rotorwash and assign a qualitative level of confidence to the range. An upper boundary defining the threshold velocity range can be estimated using figure 4 by connecting the maximum velocity values for the 9 knot data. A lower boundary can likewise be estimated by connecting the 4 foot velocity values for the 0 knot wind data. A set of mean values for each rotorcraft type can be calculated by adding these 2 values and dividing by 2. Results from the accomplishment of this task are presented in figure 6. The first observation obtained from these data is that threshold velocity ranges for 3 types of helicopters, the AH-1, UH-60, and CH-47 (at 90 degrees), are shifted toward higher velocities when compared with similiar data from the remaining 6 helicopter types. A quick review of figure 4 data indicated that for a combined total of 28 mishaps, only 5 mishaps involved the AH-1, UH-60, and CH-47. The majority of these 5 mishap reports were also very poorly documented. Since use of these suspect data in the analysis would result in separation guidelines for small helicopters being quite close to those for large helicopters (intuitively wrong), one must conclude that too few data exist for a proper analysis of the AH-1, UH-60, and CH-47 (at 90 degrees). If these suspect data are dropped from the analysis, the modified velocity boundaries are as presented in figure 7.

One can assume in analyzing the figure 7 data that the probability of the threshold rotorwash value being near the lower boundary (mid gross weight, 4 foot height, 0 knot wind) is small because the wind is rarely calm. Also, the use of this boundary would result in the specification of large separation distances in the presence of ambient winds. These large separation distances would be highly restrictive to what presently appear to be very safe heliport operations. Likewise, the upper boundary (heavy gross weight, 9 knot wind) would appear not restrictive enough. This is because separation boundaries would be based on a large value of threshold velocity, the most liberal interpretation of available mishap data. Also, no proof exists that even the majority of the reported mishaps occured in 9 knot crosswind conditions. Therefore, although based on data influenced by several key assumptions, a logical deduction is that the threshold rotorwash velocity

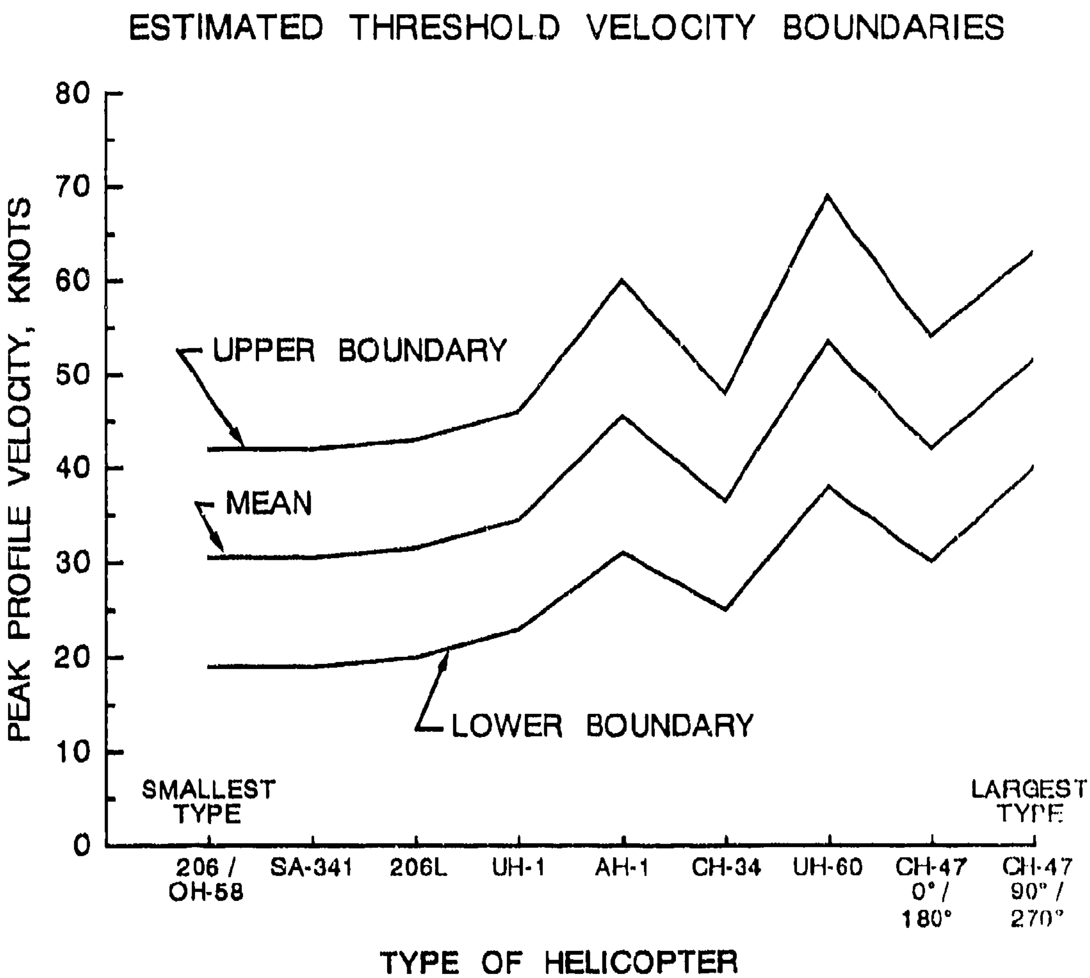

FIGURE 6 ESTIMATED THRESHOLD ROTORWASH VELOCITY MEAN VALUES AND RANGES FOR ALL HELICOPTER MISHAPS INVOLVING DOOR AND COWLING DAMAGE

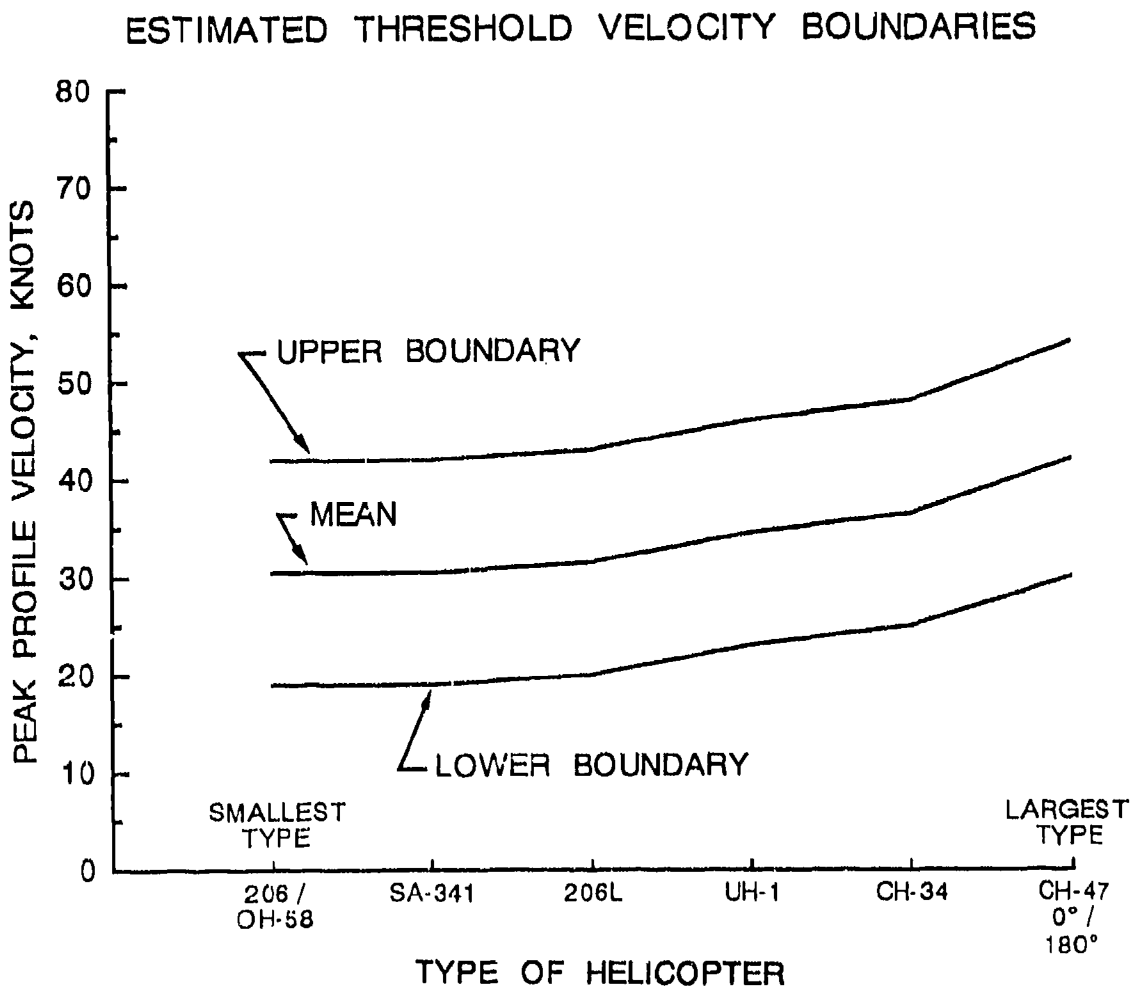

FIGURE 7 ESTIMATED THRESHOLD ROTORWASH VELOCITY MEAN VALUES AND RANGES USED IN THE FINAL ANALYSIS OF MISHAPS INVOLVING DOOR AND COWLING DAMAGE

value is between the lowest estimated mean value, approximately 30 knots, and the lowest estimated upper boundary value, approximately 40 knots.

The usefulness of any predictive methodology is only as good as its ability to correctly predict test cases. This statement is particularly true when a complex process is analyzed using a simplified model of the process. Unfortunately, no laboratory controlled test cases exist where a mishap was intentionally planned, recorded, studied, and documented. However, limited flight data do exist in reference 14 to provide clues on whether rotorwash velocities of the predicted magnitudes exist in an operational environment for the smaller classes of helicopters. These data were obtained for approximately 14 different types of rotorcraft at approximately 20 inches above ground level at both the Wall Street and Indianapolis heliports. A total of 402 individual operational movements were recorded. These movements included data for three of the nine types of helicopters for which door and cowling related mishap data were reported, the Bell 206, 206L, and UH-1. Accurate distances between the sensors and the helicopters as a function of time could not be recorded, because each helicopter was privately owned and therefore uninstrumented for test purposes. However, rotorwash velocities recorded by the sensors are representative of velocity magnitudes which would impact other rotorcraft. This is because the sensors were located in positions where other rotorcraft could have been parked.

Recorded velocity data for the Bell 206, 206L, and UH-1 models in calm winds at both heliports frequently exceeded 30 knots as the helicopters passed by the sensors. The magnitudes of some measured velocity data (for all three types of helicopters) occasionally even appeared to exceed the ROTWASH calculated peak velocities for 9 knots of wind. In some of these cases, the measured peak velocities momentarily exceeded 85 knots (approximately 100 miles per hour). As an example, a recorded movement of a UH-1 at the Indianapolis Heliport is presented as figure 8 (reproduced directly from reference 14). Reasons why these velocity values exceed peak calculated values could include effects due to maneuvering and density altitude as well as wind. It is generally accepted that peak rotorwash velocities directly in front of a helicopter during the final phase of a decelerating approach to hover are greater than those for the same helicopter after it is subsequently stabilized in hover. Also, when all other factors are held constant, peak rotorwash velocities increase with a decrease in atmospheric density (increase in density altitude). While these data do not necessarily provide specific insight into the reviewed mishaps, the data contained in reference 14 do help support many of the assumptions inherent to the analysis. This is

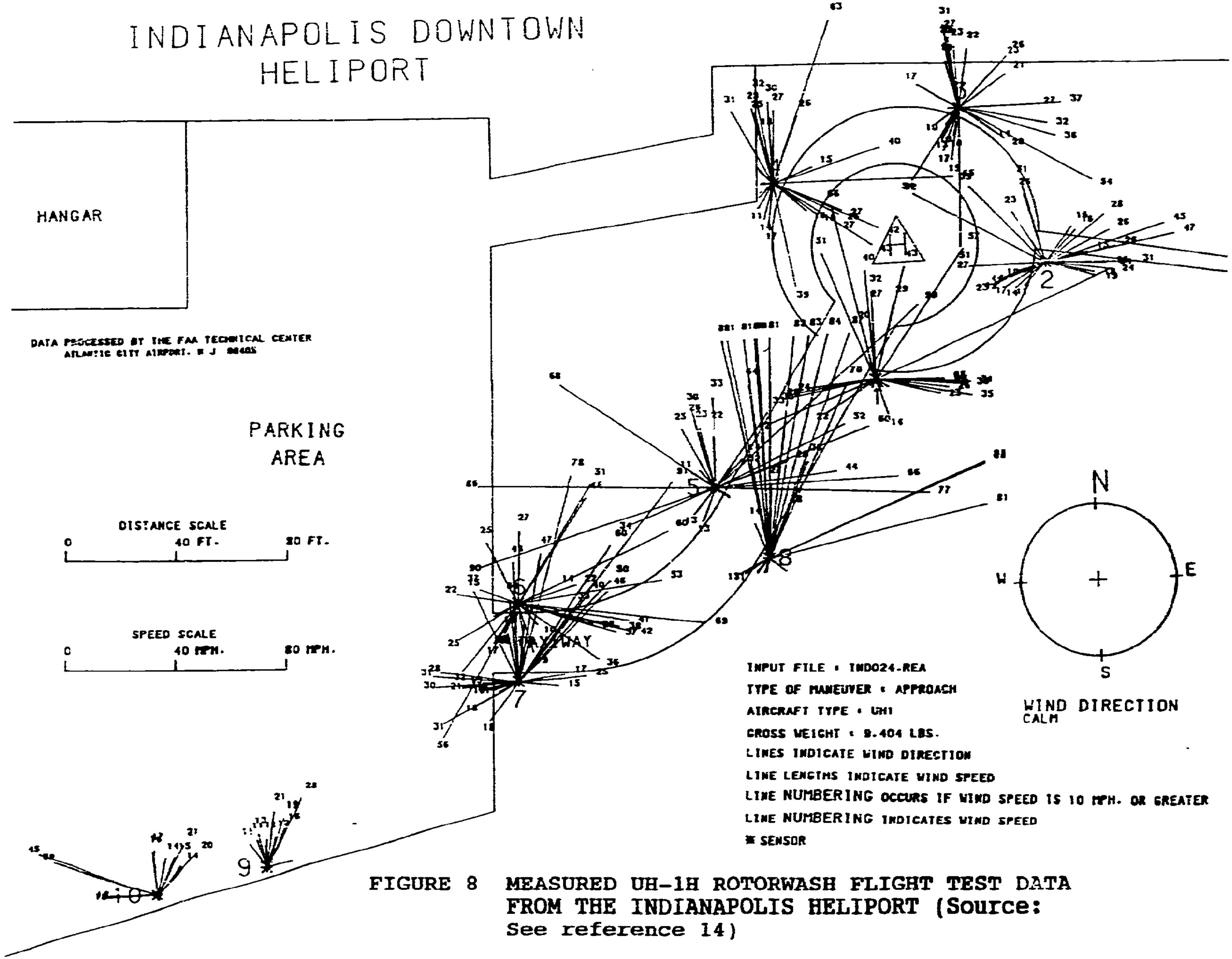

FIGURE 8 MEASURED UH-1H ROTORWASH FLIGHT TEST DATA FROM THE INDIANAPOLIS HELIPORT (Source: See reference 14)

because:

1. rotorwash peak velocities measured in an operational environment vary significantly in magnitude for the same type of helicopter. Reasons for this documented fact include pilot technique, gross weight, and atmosheric conditions (to name only a few).

2. typical rotorwash peak velocity levels in close proximity to the helicopters involved in the reported mishaps do significantly exceed the range in velocity which is expected to contain the threshold velocity value (if this observation was not confirmed by measured flight data, doubts would exist with respect to the quality of the ROTWASH calculated velocity data and the validity of the analysis approach).

3.1.3 Conclusions from the Analysis of Door and Cowling Related Mishaps

Several conclusions can be made from the presented analysis. As expected, it is impossible, using presently available test data and analytical methods, to specify and document a single threshold value of peak rotorwash velocity which, if never exceeded, is capable of preventing all door and cowling related mishaps. Instead, only a range of values can be identified which has a high probability of containing the critical value. This peak profile velocity range varies from 30 to 40 knots. Any further narrowing of this range to identify a specific threshold peak velocity value will require considerably more data, both mishap data as well as data from planned flight test experiments. Even if a narrower range is eventually identified, the decision to document a specific threshold value as a standard would be a matter of judgment since all scenarios can not be evaluated. Also, any identified "absolutely safe" value may be economically too restrictive. It may be more practical to provide a higher threshold velocity value as a guideline through educational material and rely on common sense operation of rotorcraft by operators.

3.1.4 Rotor Blade and Tailboom Strike Mishaps

The mishap summaries acquired during the reference 8 study documented numerous mishaps where rotorwash was responsible for rotor blade and tailboom damage, particularly for two-bladed rotors. The typical mishap occurred when the rotor blade of a stopped or low rpm rotor was aerodynamically induced by a passing rotorcraft's downwash to strike a tailboom or tailrotor driveshaft. This

type of mishap frequently resulted in damage to all three components of the helicopter. Unfortunately, no new mishaps were identified for analysis in this report to enhance the data base for this type of mishap. However, conclusions from the previous analysis effort do warrant summary in this report for completeness.

An additional piece of information available in studying this type of mishap was the discovery of flight manual restrictions on wind velocity for the startup and shutdown of some of the helicopters. Wind velocities specified in the flight manual restrictions were found to correlate reasonably well with threshold velocity values estimated from a study of the mishaps. Based on the restrictions specified for the CH-47, UH-1, AH-1, and OH-58 helicopters, the range of threshold peak velocity values was determined to be 30 to 37 knots. Interestingly, this range of velocity values almost exactly matches the range that was estimated for door and cowling damage. Therefore, one could conclude that specification of guideline separation distances, based on a velocity range of 30 to 37 knots, is a technically justifiable approach to minimize several types of mishaps. However, this statement must not be considered as justification to reduce the need for improved mishap data, particularly if experimentally controlled data can be obtained.

3.2 DAMAGE TO PARKED FIXED-WING AIRCRAFT

The potentially hazardous effects of rotorwash on nearby fixed-wing aircraft can be grouped in one of two categories. The first of these categories includes aircraft that are parked with their engines turned off. These aircraft may or may not be tied down. The second category includes those aircraft with engines running that are parked, taxiing, or flying in close proximity to the ground. Seven mishaps were identified for this study which fitted into one of these categories. Even though two of the reviewed mishaps did not report the exact type of fixed-wing aircraft involved, it is believed that the aircraft were light, two to four seat single engine configurations. None of the reviewed mishaps specifically stated that larger fixed-wing aircraft types were involved. The lack of a large number of reported mishaps of this type does not necessarily indicate that this type of mishap rarely occurs. There are indications that existing mishap reporting systems often overlook mishaps when a parked fixed-wing aircraft without occupants is damaged and the offending helicopter exits the mishap undamaged. Unfortunately, none of the reviewed mishap reports contained substantial detailed data for correlation of a simple analytical model of the mishap. In spite of this problem, a simple analytical model was developed to study the type of mishap where rotorwash induces a fixed-wing aircraft with the engine off to roll

over and damage one wing tip. This type of mishap had the largest number of reported incidents.

3.2.1 Mishaps Involving Fixed-Wing Aircraft With Engines Running

Three of the seven studied mishaps involved fixed-wing aircraft with their engines running. Even though reported information was minimal (not enough for a detailed quantitative analysis), the mishap scenarios are most enlightening in a qualitative sense. It is believed that their documentation in this report may be useful in preventing similiar mishaps in the future.

The first mishap reported in this category involved a tricycle gear Cessna 152 and a Sikorsky H-53 (the specific model of the H-53 was not identified). The Cessna taxied for takeoff with the intention of using runway 24 with an 8 knot wind. At the same time, the H-53 entered the landing pattern for this same runway. The Cessna then accepted the option to use runway 29 and was informed to stay clear of runway 24. The Cessna pilot taxied onto runway 29 at the intersection of the two runways, moved to takeoff position just beyond the intersection, and then braked to a stop with the tail pointed toward runway 24. The Cessna was cleared for takeoff and given the explanation that takeoff on runway 24 would have required a 3 minute wait to avoid wake turbulence from the H-53. The H-53 was then cleared to land on runway 24 behind the Cessna. When the H-53 passed by the Cessna, the Cessna tail lifted up and the airplane nosed over on runway 29. Damage to the Cessna was reported as substantial. The runways involved were reported to be 150 feet wide. Key unknown factors in the mishap are the specific model of H-53 involved (two or three engine version), the airspeed of the H-53, the exact distance between the two aircraft at the closest point, and whether or not the H-53 passed by in the air (at what altitude?) or on the ground. Without these pieces of information, a quantitative analysis is almost futile. However, if several assumptions are made, an estimate of the rotorwash velocities involved can be attempted.

If the H-53 was at a very low airspeed and almost on the ground when it passed the Cessna, one might assume that the H-53 was approaching hover. This is probably the worst case scenario from a rotorwash estimation standpoint. In this instance, peak profile velocity flight test data from reference 11 can be used to estimate the rotorwash velocities involved. These velocity data are presented in figure 9 (reproduced directly from reference 11). If the Cessna was between 100 and 200 feet away (which is highly probable), peak velocity values may have been between 40 and 60 knots. If the H-53 was flying at a low airspeed, such as 30 knots, the rotorwash flowfield would have been composed

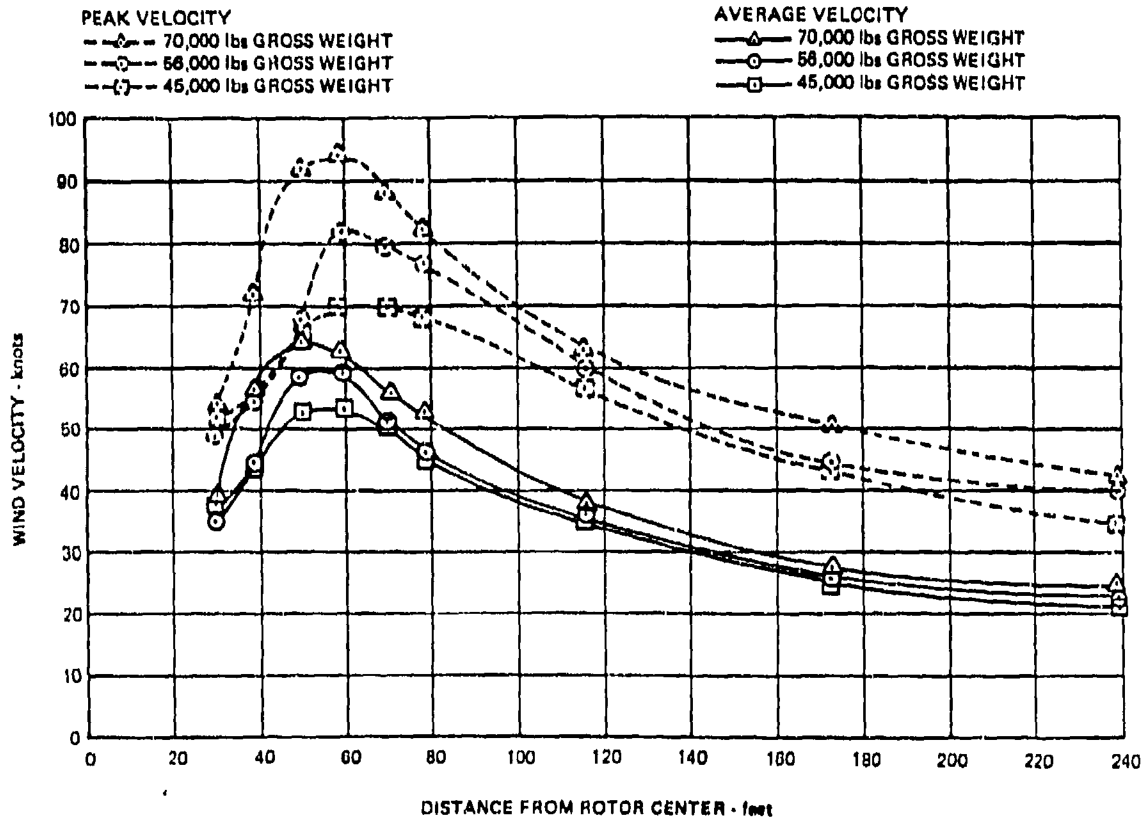

FIGURE 9 MEASURED CH-53E PEAK PROFILE VELOCITIES AS A FUNCTION OF DISTANCE FROM THE ROTOR CENTER AT A HEIGHT OF 3 FEET FOR A HOVER WHEEL HEIGHT OF 20 FEET (Source: See reference 11)

of a trailing wake vortex structure. Data from reference 18 for a Sikorsky CH-54 (which has a rotor configuration almost identical to an H-53) are presented in figure 10 to provide insight into wake velocities contained within this type of flowfield. These presented data are for a gross weight of approximately 38,000 pounds at an airspeed of 30 knots. Peak velocities in this wake structure taken at 28 seconds behind the CH-54 are between 15 and 20 meters per second (29 and 39 knots). It is reasonable to assume that these velocities could be increased by as much as 50 percent if the gross weight of the H-53 was greater than 38,000 pounds

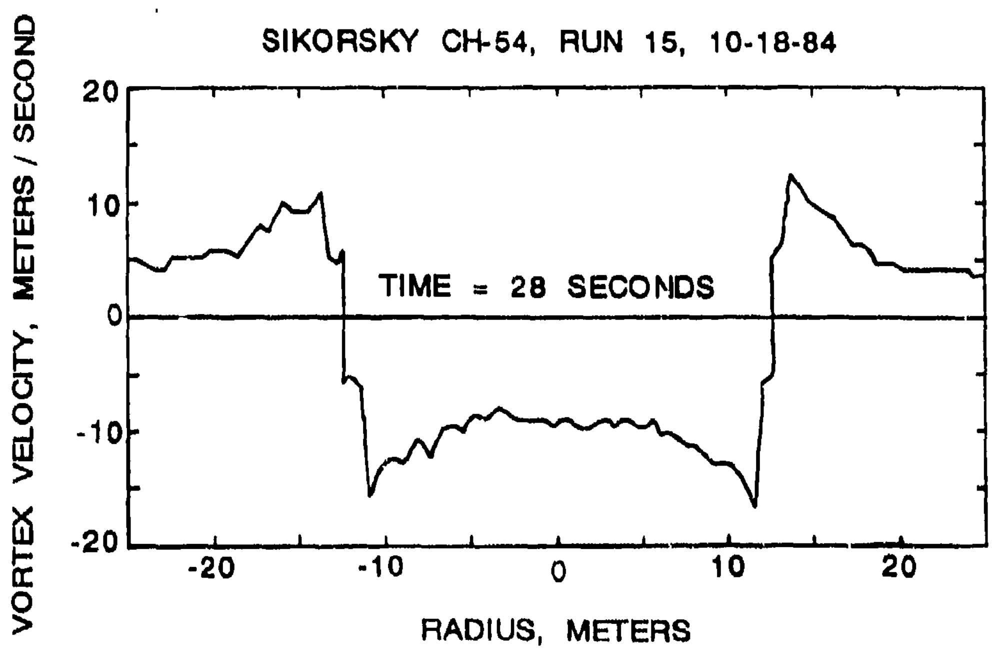

FIGURE 10 CH-54 TRAILING WAKE VELOCITY PROFILE AT AN AGE OF 28 SECONDS (Source: See reference 17)

or if the wake data were measured within seconds after the helicopter passed by. In summary, if the Cessna 152 was struck by rotorwash flowfields of either type containing velocities of the estimated values, there is little doubt that the aircraft could have been turned over (as was actually the case). More discussion on the significance of these velocity magnitudes is presented in the following paragraphs.

The second mishap in the category of aircraft with engines running occurred between a Sikorsky UH-60 helicopter and a tricycle gear Piper PA-28. The PA-28 landed at a gliderport and was either taxiing or holding position on the ground in an 8 knot wind when the UH-60 reportedly "swooped" down next to the PA-28. The UH-60 mistakenly intercepted the PA-28 as a drug smuggling aircraft and the officers on the helicopter were trying to make an arrest before the

pilot could get away. No other details were given, other than substantial damage was incurred by the PA-28 and the government admitted their liability. Little can be learned from this mishap other than the fact that UH-60 series helicopters are clearly capable of overturning PA-28 size aircraft (which has a maximum gross weight of 2,150 pounds with four passengers; only the pilot was aboard in this incident).

The third reported mishap involved an unusual set of circumstances. In this mishap, a Cessna 152 and a helicopter were both destroyed while in the air. An analysis of this accident is clearly beyond the capabilities of available analytical tools; however, it is hoped that mention of the known factors in the mishap will someday help to prevent a similiar incident. The Cessna was engaged in the practice of takeoffs and landings with a student pilot and instructor on board. Winds were approximately 8 knots. As the Cessna entered the turn on final to runway 3, radio calls were made to a helicopter approaching the uncontrolled airport. These calls were apparently never heard by the helicopter pilot as he came to a hover near the taxiway parallel to runway 3. As the Cessna lifted off after the touch and go landing, it veered to the right and collided with the helicopter. The flight instructor survived the mid-air collision and stated that control of the Cessna was lost when it flew through rotor wake turbulence.

The lesson to be learned from this mishap is that hovering rotorwash can even be dangerous to small aircraft that are at flying speeds where aerodynamic controls are quite effective. Therefore, specification of criteria for separation of rotorcraft and fixed-wing aircraft will need to take into account airborne separation distances from hovering rotorcraft. Unfortunately, at this time virtually no data exist, either analytically or experimentally obtained, which can be used to help define separation distances for this type of mishap scenario.

3.2.2 Mishaps Involving Fixed-Wing Aircraft With Engines Turned Off

Five mishaps were reviewed involving fixed-wing aircraft on the ground with engines turned off. In three of the mishaps, the fixed-wing aircraft rotated about its longitudinal axis and one of the wingtips struck the ramp. In one instance, one side of the wing was tied down and the other side was untied. In the fourth mishap, the airplane rotated so that the empennage struck the ramp. The exact nature of the damage in the fifth incident was unreported. After a review of the mishap reports, the reader is left with the impression that parts of the damaged aircraft momentarily became airborne before the aircraft suddenly and uncontrollably rotated about an axis and were damaged.

Three of the mishaps involved Bell UH-1 helicopters and two involved Boeing CH-47s. Wind appears to have been a contributing factor with rotorwash in at least four of these accidents; three were reported with winds in excess of 10 knots (direction of the wind was unclear, however). Damage costs reported in two of these mishaps, both involving wing tips, were $200 and $550, respectively. The three known damaged fixed-wing aircraft were Cessna 150, 172, and 175 models. In several of the mishaps, undamaged fixed-wing aircraft were reported tied down next to the damaged aircraft. Unfortunately, documented details for all five of the reported mishaps were insufficient to analytically study each mishap as a separate incident. However, the mishaps do provide guidance when studied as a group. Further discussion is presented on this subject in the next section.

3.2.3 Analytical Model for Overturning Fixed-Wing Aircraft

The analytical model developed to investigate fixed-wing overturning mishaps uses simple aerodynamic theory. The model is formulated for analysis of only those mishaps where the aircraft rolls about its fuselage and a wingtip strikes the ground. Mishaps where the empennage is lifted up and the nose strikes the ground are not modeled. The modeling approach developed in this section is a continuation of work originally developed and presented in reference 8. The forces described by the model are depicted graphically in figure 11.

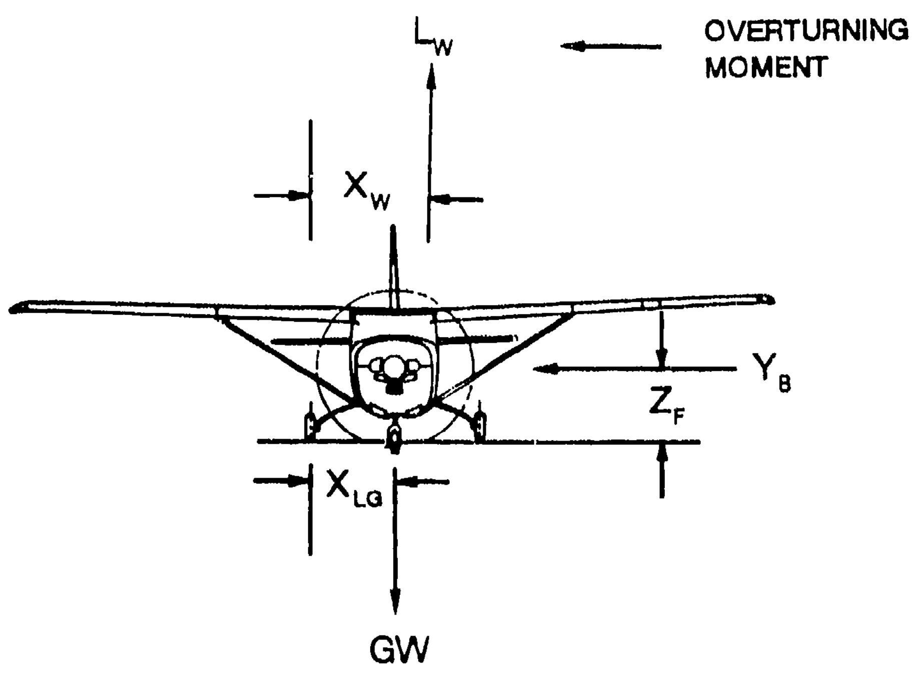

FIGURE 11 FORCES MODELED TO STUDY THE OVERTURNING OF LIGHT FIXED-WING AIRCRAFT

The mathematical model assumes that the fixed-wing aircraft is a small high-wing civilian type, such as a Piper PA-18 Cub or a Cessna 172. These two aircraft are representative of thousands of civilian aircraft in use today in the United States. Mathematically, these aircraft are also the most susceptable to rotorwash-induced overturning moments. No specific types of homebuilt aircraft were analyzed for this report, because wing loadings for these types of aircraft are comparable to those for the PA-18 or Cessna 172.

The two aerodynamic components of the fixed-wing aircraft overturning moment, as mathematically modeled in this section, are those which result from lift (due to the wing) and body axis side-force (which is composed of wind axis side-force and drag components). The modified mathematical model uses low angle-of-attack wind tunnel data at sideslip angles up to 90 degrees from a high-wing tricycle gear aircraft configuration (not built). The source for these data was identified subsequent to the work presented in reference 8. These data indicate that maximum rolling forces about the fuselage body axis exist at approximately 20 degrees sideslip. The simple equation which equates the overturning aerodynamic moments to the stabilizing moment due to gross weight at the instant prior to overturning is:

$$(GW)(X_{LG}) = (L_W)(X_W) + (Y_B)(Z_F) \qquad (1)$$

where:

GW = manufacturer's stated empty weight + 50 lb

X_{LG} = moment arm of the gross weight about the landing gear (one-half the wheel stance), ft

L_W = wing lift, lb

X_W = moment arm from the wheel to the point of application of the wing center of lift (this is conservatively estimated for a wing at a 20 degree yaw angle with a dihedral effect to be: $X_{LG} + (1/15)(b_W/2)$, where b_W is the wing span in ft), ft

Y_B = fuselage body-axis aerodynamic side-force, lb

Z_F = vertical moment arm from the wheel to the point of application of the side-force on the aircraft fuselage, ft

No assumptions are made in this equation with respect to forces created by the horizontal tail. Also, no reduction in the landing gear pivot arm is accounted for if the rollover occurs along the line intersecting one main wheel and the tail or nose wheel (which is the more likely occurrence). The 50 pounds added to the gross weight term (GW) are provided to account for residual fluids and miscellaneous items aboard an aircraft over and above the manufacturer's stated empty weight. Developing the equation further, it can be shown that:

$$\alpha_W = \frac{(GW)(X_{LG}) - (C_{Y_\beta})(q)(S_W)(Z_F)}{(q)(S_W)(a_{3d})(X_W)} \qquad (2)$$

where:

α_W = wing angle-of-attack, deg

C_{Y_β} = non-dimensional aerodynamic side-force coefficient

q = $(0.5)(\rho)(V^2)$ where ρ is the atmospheric density in slugs/ft^3 and V is the air velocity in ft/sec

S_W = wing area, ft^2

a_{3d} = wing 3-dimensional lift curve slope (at a 20 degree sideslip angle), 1/deg

Once values are calculated for the constant aerodynamic and geometry terms, equation 2 can be evaluated. This task is accomplished by substituting a range of values for V, the air velocity. A graph of the minimum required wing angle-of-attack necessary to overturn the aircraft versus air velocity is the resultant output.

The data presented in figure 12 represent the estimated angle-of-attack values required to overturn a Piper PA-18 or Cessna 172 as a function of rotorwash peak velocity. Table 3 presents a summary of the input data values used to make these calculations. These results indicate that slightly lower values of rotorwash than were previously predicted in reference 8 may be capable of overturning light fixed-wing aircraft. At air velocities of approximately 40 knots, only 6 to 8 degrees of wing angle-of-attack are required to overturn the aircraft. Angle-of-attack values of this magnitude are frequently measured in hover rotorwash flowfields. This is because the flowfields have a tendency

to expand upward as the flow speads out across the ground. Figure 13 presents measured flight test data (reproduced from reference 11) which confirm that the velocity vectors in a CH-53E rotorwash flowfield have an oscillatory upward component of velocity at a wheel height of 20 feet and a gross weight of 45,000 pounds.

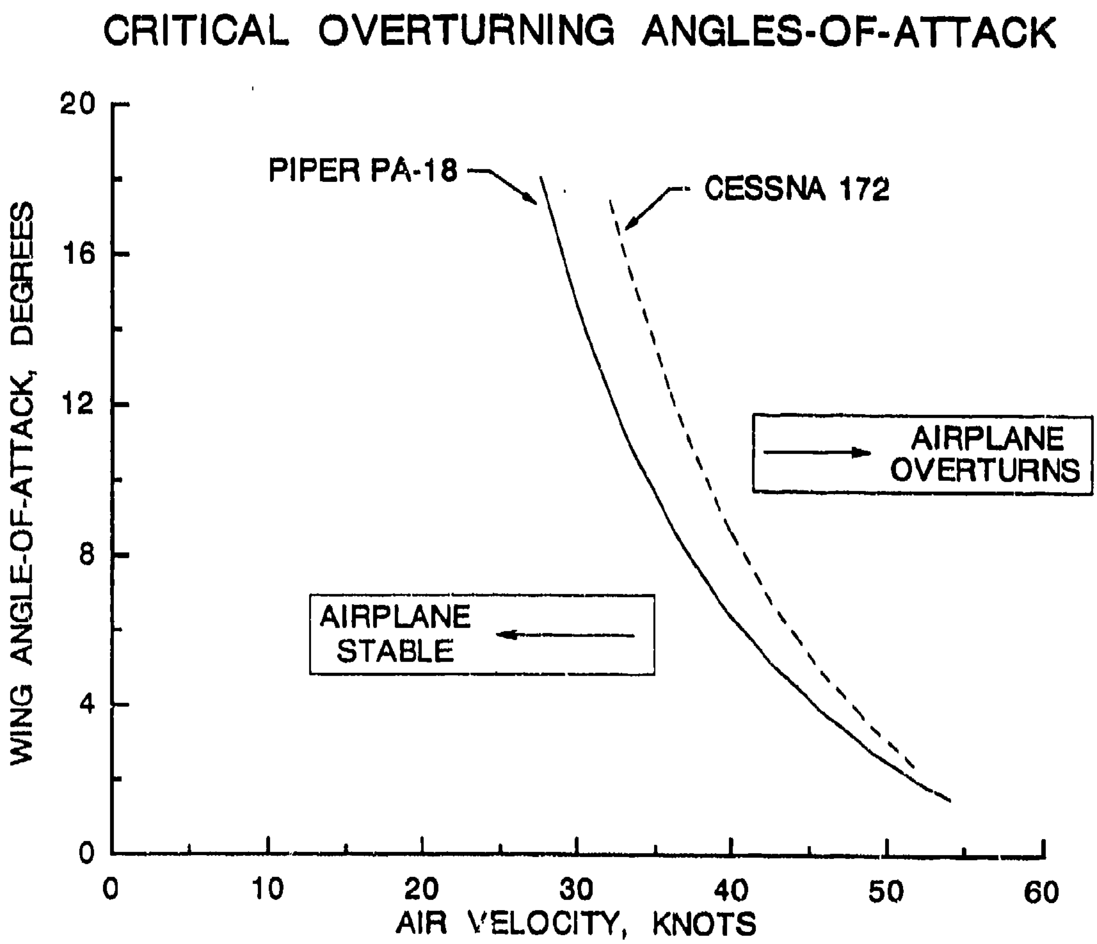

FIGURE 12 MINIMUM AIRSPEED/ANGLE-OF-ATTACK REQUIREMENTS FOR THE OVERTURNING OF LIGHT FIXED-WING AIRCRAFT

TABLE 3 INPUT DATA VALUES FOR MODELED FIXED-WING AIRCRAFT

PARAMETER	PIPER PA-18 VALUE	CESSNA 172 VALUE	UNITS
Gross Weight (GW)	980	1300	lb
Moment Arm for Weight (X_{LG})	3.0	4.0	ft
Air Density (ρ)	0.00226	0.00226	$slug/ft^3$
Wing Area (S_W)	178.5	174	ft^2
3-d Lift Curve Slope (a_{3d})	0.072	0.072	1/deg
Side-Force Coefficient (C_{Y_β})	0.43	0.43	-ND-
Moment Arm for Lift (X_L)	3.18	4.18	ft
Moment Arm for Side-Force (Z_F)	3.0	6.0	ft

The next logical step in the development of this analysis would be an attempt at correlation of the model with actual mishap data. Unfortunately, as discussed earlier, the reported mishaps did not contain enough information for detailed analysis. In one mishap involving a Bell UH-1H, the separation distance with the damaged Cessna 172 was reported as 100 to 130 feet. However, the confusing factor in this report was that the Cessna was reported upwind of the helicopter in winds gusting up to 30 knots. Simple calculations indicate that this reported piece of information is somewhat contradictory. Therefore, it is effectively impossible to define the type of flowfield to be used for any detailed analysis. If the Cessna had been reported downwind of the helicopter with 9 knot winds, then rotorwash velocities would be predicted between 35 and 40 knots at 8 feet off the ground and higher at lower heights. The estimated critical angle of attack at 40 knots is 8.5 degrees. Most Cessna aircraft have a 1 to 3 degree geometric angle-of-attack, a negative zero lift line offset (-2 to -3 degrees), as well as 1 to 2 degrees dihedral. Therefore, an effective angle-of-attack of 8.5 degrees could be easily obtained.

The only other mishap in which a reported distance was specified was one involving a Boeing CH-47. The exact type of civilian fixed-wing aircraft was not reported. The wind was described as 12 to 15 knots, and the CH-47 was directly

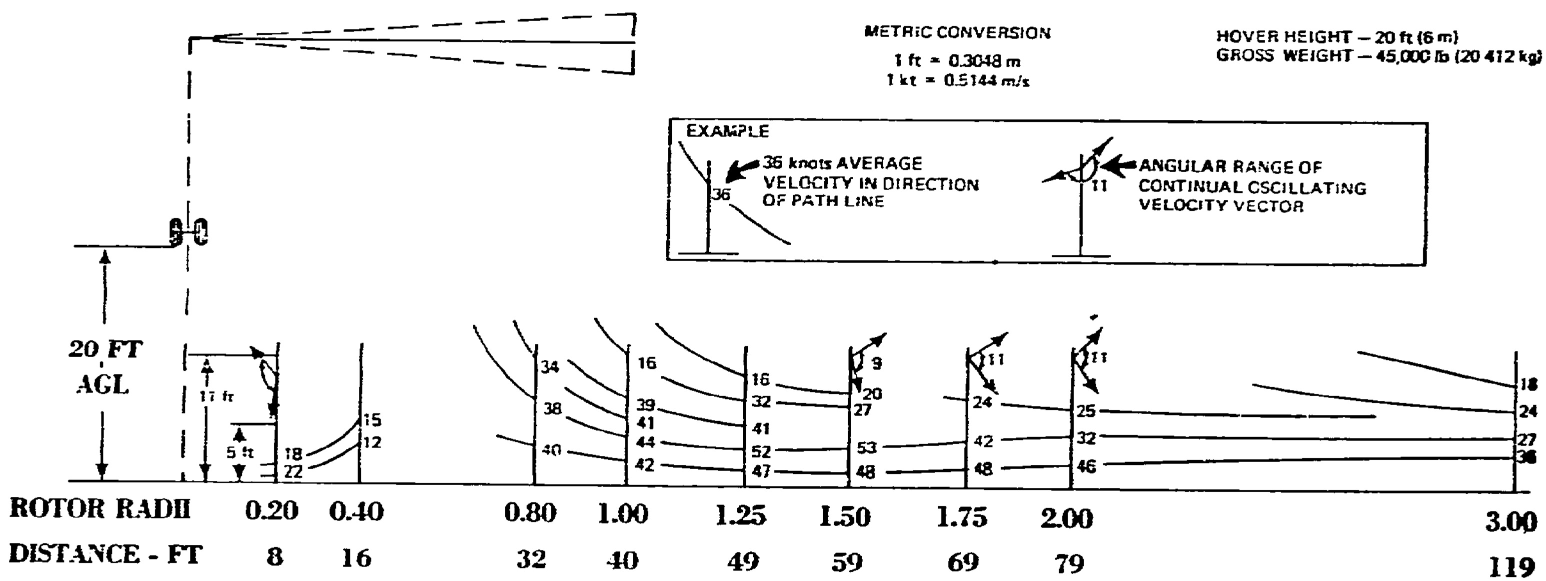

FIGURE 13 CH-53E ROTORWASH VELOCITY STREAMLINES
(Source: See reference 11)

upwind of the fixed-wing aircraft at approximately 225 feet. Estimated CH-47 rotorwash velocities at this distance are approximately 36 to 53 knots. This broad range of predicted velocities results because the CH-47's orientation with respect to the fixed-wing aircraft is unknown. Predicted **velocities for tandem rotor configurations** along the **fuselage** centerline are significantly lower than those predicted along a line at 90 degrees to the centerline. If the fixed-wing aircraft was similiar to a Piper PA-18 or Cessna 172, the estimated critical angle-of-attack would be between approximately 1 and 10 degrees. This angle-of-attack range could easily be encountered in a rotorwash flowfield. The Piper PA-18 and almost all other aircraft with tail wheel configurations have a geometric angle-of-attack of over 12 degrees when parked on the ramp.

3.2.4 Conclusions from the Analysis of Fixed-Wing Overturning Related Mishaps

In conclusion, several different types of rotorcraft induced fixed-wing mishaps have been reviewed. Analytical methods for the prediction of safe separation guidelines for some of these types of mishaps do not presently exist (i.e. for rotorwash lifting the tail of a fixed-wing aircraft). The most frequently reported mishap involves parked fixed-wing aircraft which are damaged near the wingtip after rotorwash rotates the aircraft about its fuselage. A simple methodology has been developed for an analysis of this mishap. This methodology estimates the wing angle-of-attack value required to overturn a light fixed-wing aircraft when the rotorwash velocity is specified. Examples of the use of this methodology are presented. Analysis indicates that if predicted critical angles-of-attack for a specific rotorwash velocity are less than 10 to 12 degrees, trends based on mishap data show that rotorcraft are too close to unsecured fixed-wing aircraft. Unfortunately, due to a lack of detailed information in the mishap reports, none of the reported mishaps could be used to conclusively validate the developed methodology.

3.3 MISHAPS INVOLVING OIL DRUMS

Two mishaps involving oil drums were studied as examples of mishaps which occur when rotorwash upsets large objects. These types of mishaps can be very serious because they usually occur unexpectedly and the large object mass can produce serious damage. More often than not, the mishaps also involve objects which have large exposed surface areas which would not normally be expected to be overturned by rotorwash.

The first of the two analyzed mishaps involved the overturning of a 55-gallon oil drum by a Bell UH-1H at an airport refueling site. The drum was overturned and blown

across the ground approximately 20 feet into a parked automobile. The UH-1H hover taxied by the drum at a distance estimated to be 55 feet while repositioning for takeoff. The damage claim in this mishap was minor, only $103.40, but it could have been much more serious had something or someone else been struck. The second mishap involved a Bell 206L LongRanger and an empty oil drum on an offshore drilling rig. The drum, which was supposed to have been tied down, was blown over and off the edge of the rig helipad during the takeoff. The drum landed on a vessel which was making repairs to the rig. An undisclosed injury was subsequently reported for a crewman. Total damages, if any, were not disclosed.

3.3.1 Analytical Model of Mishaps Involving Oil Drums

The first task in the detailed analysis of these two mishaps was to acquire information on the amount of applied moment required to overturn an empty oil drum. Since information of this type was not found in any reference book or report, a simple experiment was conducted to measure the moment. The 55-gallon drums used in the experiment were located in a park on a grass surface and were being used as waste receptacles. The measured overturning force was applied to the top of the drum through a harness fitted around the drum. This force was measured with a calibrated spring force gauge and multiplied by the moment arm of 33 inches to obtain the overturning moment. Drums containing varying levels of refuse were measured, as well as empty drums; the results are presented in figure 14. However, several factors must be considered prior to use of these data. These factors are as follows:

1. it was apparent during the experiment that the weight of the refuse in the drums had a significant impact on the results,

2. drums which were more than one-half full sometimes tended to slide across the grass and were not inclined to overturn as easily, and

3. if water or oil had been contained in the bottom of the drums, which was not the case in this experiment, the fluid would have significantly increased the measured overturning moment. The drums would then be more likely to slide before overturning if they were not constrained along the bottom edge.

The second task in the analysis was to estimate a generic velocity profile that would produce the required overturning moment for an empty oil drum, approximately 28 f

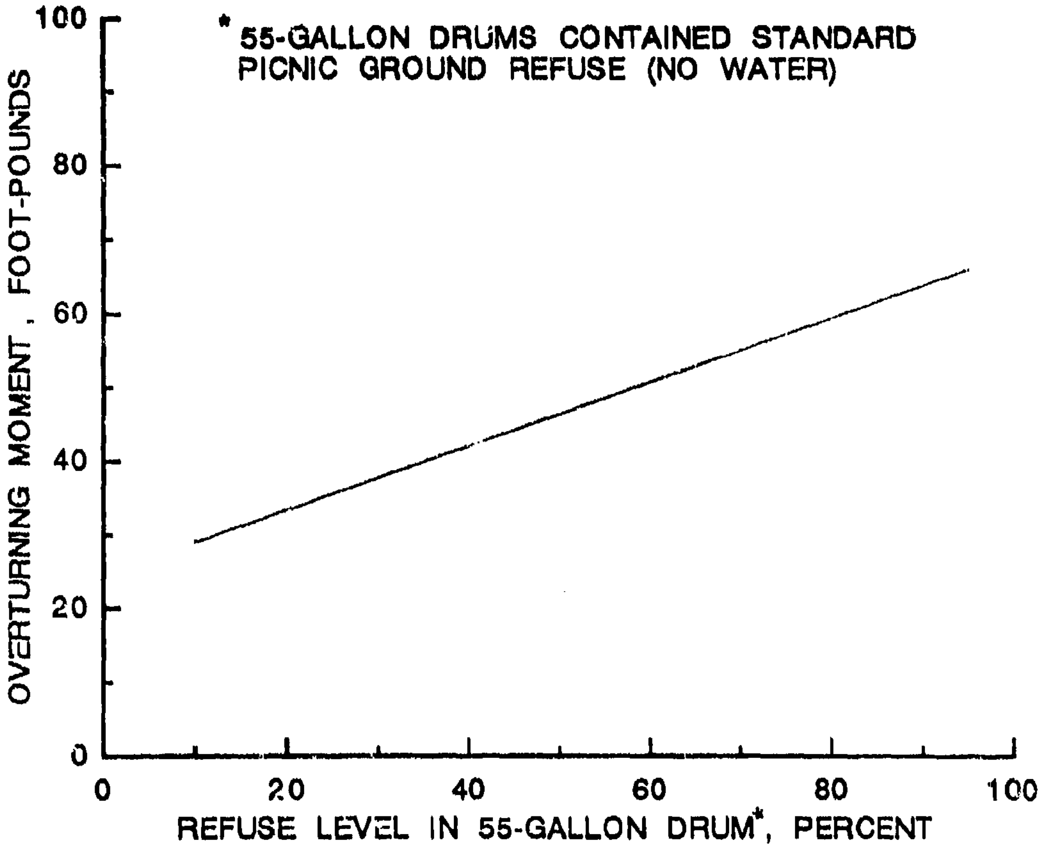

FIGURE 14 55-GALLON OIL DRUM OVERTURNING MOMENTS

foot-pounds. This task was accomplished by dividing the drum into 17 equal segments and iteratively integrating calculated UH-1H velocity profiles from 0 to 33.5 inches until the calculated overturning moment exceeded the critical value. The total projected drum surface area used in these calculations was approximately 5.3 square feet (this value was based on the maximum diameter of the drum and did not take into account the effect of the ridges along the side which slightly reduced the projected area). The coefficient of drag (C_D) was estimated as approximately 0.65 from reference 19. The air density used in the calculations was 95 percent of sea level standard day conditions. The approximate generic velocity profile found to produce the critical overturning moment value using the above values is presented in figure 15. The peak velocity in this profile is approximately 47 knots at a height of 8 to 10 inches off the ground and is reduced to approximately 38 knots at 33.5 inches. If a constant velocity profile is assumed for the sake of simplicity, the critical velocity is approximately 43 knots. With completion of this task, it was then possible to further analyze the two oil drum mishaps.

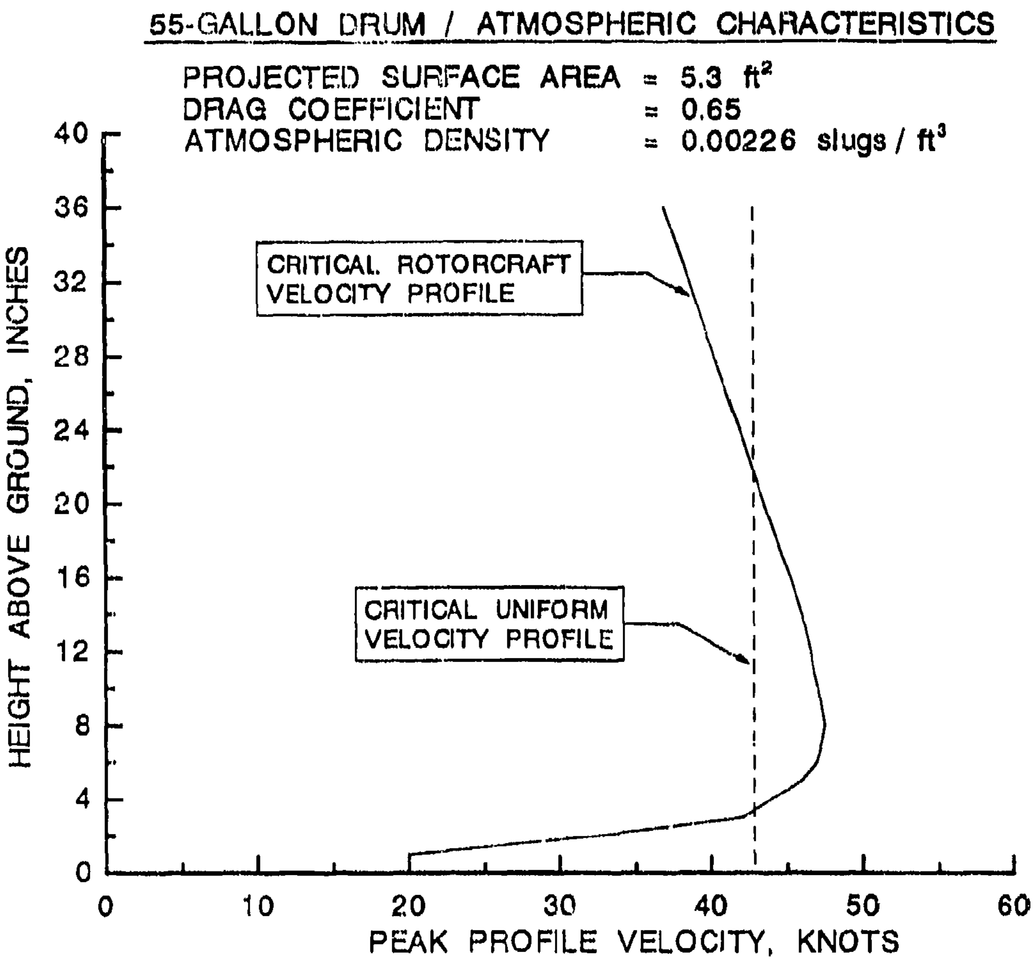

FIGURE 15 GENERIC VELOCITY PROFILE CREATING THE MOMENT REQUIRED TO OVERTURN A 55-GALLON OIL DRUM

3.3.2 Analysis of Mishaps Involving Oil Drums

The distance at which the critical velocity profile characteristics are exceeded for the mishap involving the UH-1H and the automobile is determined from figure 2. If the peak hover velocity curve for a 0 knot wind is reviewed, the 47 knot threshold is not exceeded unless the oil drum is less than 42 feet away. This result would be expected, since the probability of a no wind condition is small. Along the 9 knot wind curve, the peak velocity is exceeded at distances less than approximately 90 to 100 feet. This result would indicate that the ambient wind occurring during the mishap was probably less than 5 knots. Unfortunately, the actual wind was not recorded. It would also be presumptuous to assume that this analysis approach is so exact as to be capable of predicting the actual wind condition. However, when one considers the large number of

unknowns related to the mishap (i.e., gross weight, actual distance to drum, wind direction and velocity, etc.), these results do indicate that the analysis appears capable of predicting quite reasonable results for this specific mishap.

The second reported mishap was analyzed in much the same way as the first. The most significant unknown in the description of the mishap was the distance between the oil drum and the 206L during takeoff. Since this information was not available, a search was initiated for as many photos as could be obtained on short notice of helicopters on oil rigs. Industry requirements for these types of helipads specify that the minimum dimension of the pad be no less than the diameter of the rotor of the largest helicopter that will use the pad. In looking at the photographs, the helipads appeared, on average, to be approximately 1.25 times the diameter of most of the helicopter rotors. Also, many of the pads in the photographs showed Bell 212 helicopters somewhere in view. If the diameter of a Bell 212 rotor (48 feet) is multiplied by 1.25, the resulting pad minimum dimension would be exactly 60 feet. While this logic does not confirm the size of the pad in the 206L mishap, it does appear to make sense as a reasonable pad size. The diameter of the 206L rotor is 37 feet and it would be unlikely that the critical dimension would be sized for such a small helicopter (pilot + up to six passengers). Also, the pad obviously had to have enough extra room to safely accommodate other objects, such as an oil drum.

Assuming a pad size of 60 X 60 feet, if the 206L was centered on the pad, the oil drum would be approximately 30 feet from the center of the rotor or 12 feet from the tip of the rotor. If the helicopter was not centered on the pad, this distance could probably be increased by as much as 10 feet. A review of 206L rotorwash characteristics using a chart similiar to figure 2 indicates that the oil drum will overturn if it is located within 45 feet of the center of the rotor in a 9 knot wind. The drum will also overturn at distances of up to 30 feet in a 5 knot wind. These estimates of the critical distance appear to be very sensible in light of the few known facts about the mishap.

3.3.3 Conclusions for Mishaps Involving Oil Drums

Two conclusions result from the mishaps which have been analyzed in this section. The most important of these conclusions is that objects which might normally be considered to be immoveable by most civilian personnel and many pilots are, to the contrary, quite moveable and potentially dangerous. This statement is justified by the simple fact that the mishaps occurred and were caused by light to medium class helicopters. Therefore, the rotorcraft community should be prepared to devote their

attention toward the prevention of similiar types of "unlikely" mishaps.

A second conclusion is that the probability of occurrence for this type of mishap can be somewhat reliably predicted. This type of task can be analyzed using simple analytical models which are based on the physics of the problem and straightforward assumptions. In mishaps involving empty oil drums, the critical rotorwash velocity is approximately 43 to 47 knots. This does not mean that the developed methodology is completely validated at this point in time with sufficient experimental data to ensure that all similiar mishaps can be prevented. Improvements to this methodology can be achieved if several carefully controlled experiments are conducted to acquire documented flight test data.

3.4 DAMAGE TO GROUND VEHICLES

Mishaps involving ground vehicles can usually be classified in one of three groups. The first group involves mishaps where objects are blown into vehicles. Damage can be caused by large objects, i.e. the oil drum mentioned in the previous section, or small objects such gravel or sand which result in scratched paint or broken glass. The reader is referred to reference 8 for documentation of a mathematical model and further discussion with respect to this type of mishap. The second group of mishaps involves damage to camper shells (on pickup trucks) and automobile sunscreens (commonly found on hatchback models). The last group of mishaps involves damage to small vehicles, i.e. motorcycles.

3.4.1 Mishaps Involving Camper Shells and Automobile Sunscreens

Three mishaps involving damage to camper shells and automobile sunscreens were identified for possible analysis in this study. In two of the mishaps, a Bell UH-1 overflew a parking lot and the camper shell was reported to have blown off the back of a pickup truck onto other cars. In one instance, the UH-1 was reported at approximately 25 to 30 feet above the parking lot. In the second mishap, the camper shell was reported to have been attached with 1/2 inch bolts without washers. No other significant details were provided. The only lesson which can be learned from these two mishaps is that camper shells are susceptible to damage or destruction by rotorwash.

The mishap involving an automobile sunscreen occurred in a parking lot adjacent to a hospital helipad (helipad dimensions were 90 x 116 feet). The automobile was parked approximately 40 to 45 feet to the right of the helipad approach path. As a Sikorsky S-76 approached the pad for a

landing, the sunscreen was blown up and off the rear window of the car. The sunscreen was reported to have been unlatched at the time and the hinges were broken off during the mishap. The altitude of the S-76 when it slowly passed the car was reported at 40 to 50 feet AGL. Atmospheric conditions at the time are unknown.

Using the above reported information, a simple analysis of the mishap was conducted. If the wind was calm at the time of the incident, estimated peak rotorwash velocities, depending on the actual height of the car, could have been between 45 and 55 knots. This estimate also assumes that other cars were not parked between the damaged car and the helicopter (available analysis tools will not estimate velocities for complex scenarios). The predicted velocities could have been as high as 70 knots if the ambient wind was blowing at 9 knots toward the car from the direction of the S-76.

The most likely conclusion which can be made from this simple analysis is that the sunscreen was probably blown off by a lower rotorwash velocity. The unknown threshold velocity was probably generated when the helicopter was farther out on the approach path. Even if the S-76 was 45 feet away when the sunscreen separated from the car, there is a finite time lag for air molecules to travel from a helicopter to the car during a landing maneuver. Therefore, the specification of guidelines for prevention of this type of mishap will require more research.

3.4.2 Mishaps Involving Motorcycles

Two mishaps involving motorcycles were identified for analysis. Both mishaps involved unknown ambient winds and S-76 helicopters which were reported at mid gross weight. In the first mishap, the S-76 landed at a county park in a picnic area on an unprepared surface. While the S-76 was at 15 feet AGL, the motorcycle (type unknown) overturned at a distance of approximately 40 feet. The orientation of the motorcycle to the helicopter was not reported. In the second mishap, the S-76 landed at the same hospital helipad as was mentioned in the previous section. The overturned Harley-Davidson motorcycle was parked so that the left side of the motorcycle was pointed toward the passing helicopter. The distance between the helicopter and motorcycle was approximately 70 to 75 feet. The helicopter was reported at 40 to 50 feet AGL when it passed the motorcycle. Windshields and paint were damaged in both overturning mishaps.

The first task in the analysis of the motorcycle mishaps was to experimentally measure the overturning moments for a Harley-Davidson motorcycle. The smaller model Harley-Davidson was chosen to ensure that the measured

moments were probably the lowest that would exist for this brand of motorcycle. Moments were measured using the same equipment and techniques used to measure the oil drum overturning moments. The overturning moments were measured in the direction away from the kickstand, since the motorcycle overturns much easier in this direction. This is also the direction the Harley-Davidson reportedly overturned in the second mishap. The overturning moment measured with the front wheel turned toward the kickstand was approximately 117 foot-pounds. With the wheel turned away from the kickstand, the measured moment was considerably less, approximately 66 foot-pounds. Overturning moments for the numerous other types of motorcycles were not measured. However, it is quite probable that the critical moment values for some of these motorcycles are less than 66 foot-pounds.

The second task in the analysis was to develop a simple mathematical model to describe the mishap. In this model it is assumed that the overturning moment due to a component of the motorcycle weight (due to the tilt of the motorcycle on the kickstand) will be exactly counteracted at the instant of overturning by an applied aerodynamic moment. The simple equation describing this relationship is:

$$M_W = (Z_A)(F_A) \qquad (3)$$

where,

M_W = measured motorcycle overturning moment, ft-lb

Z_A = moment arm of the applied aerodynamic moment, ft

F_A = applied aerodynamic force, lb

This equation can be further developed to calculate the overturning velocity required by substituting equation 4 into equation 3.

$$F_A = (S_M)(C_D)(0.5)(\rho)(V_C)^2 \qquad (4)$$

The resulting equation is:

$$V_C = \sqrt{\frac{M_W}{(1.43)(Z_A)(\rho)(S_M)(C_D)}} \qquad (5)$$

where,

V_C = critical overturning velocity, knots (the 1.68894 ft/sec to knot conversion is included in the equation)

ρ = air density, slug/ft^3

S_M = projected side area of the motorcycle, ft^2

C_D = motorcycle non-dimensional drag coefficient

Equation 5 was analyzed for a range of values for both the motorcycle drag coefficient and the length of the applied aerodynamic moment arm on the motorcycle. Exact values for these parameters are unknown for a Harley-Davidson. The value of the drag coefficient was varied from 0.25 to 1.0, and the length of the moment arm was varied from 2.3 to 2.9 feet. The air density used was 0.00226 slugs/ft^3. The roughly estimated projected side area from measurements of the motorcycle was 17.5 ft^2. Figure 16 presents a summary of the calculated results.

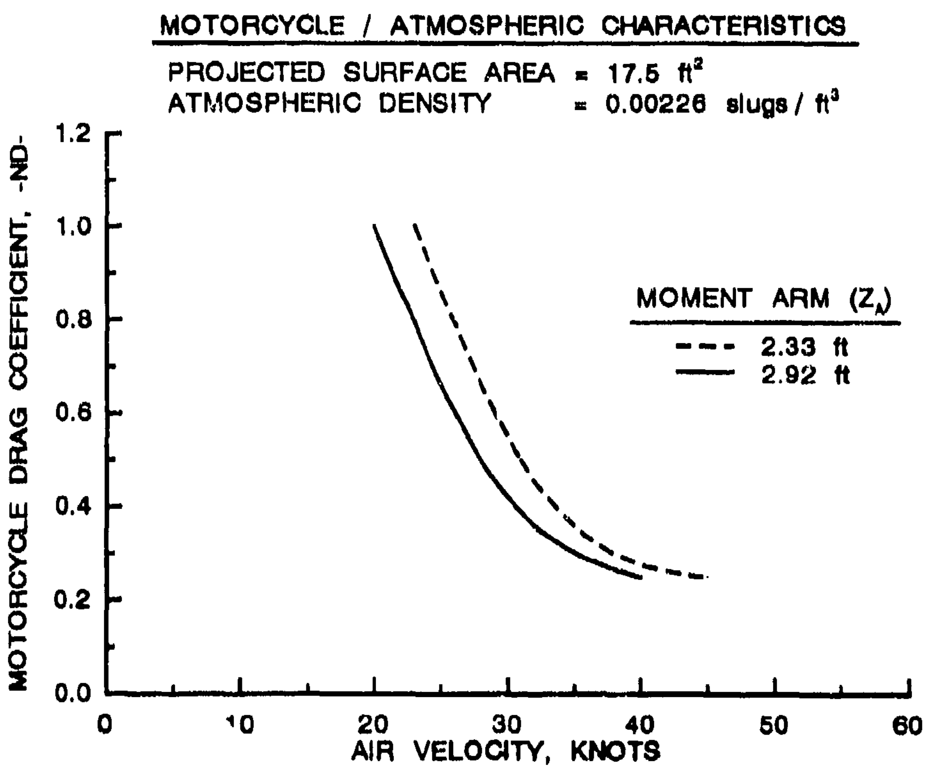

FIGURE 16 ESTIMATED THRESHOLD OVERTURNING VELOCITIES FOR A MOTORCYCLE AS A FUNTION OF DRAG COEFFICIENT AND APPLIED MOMENT ARM LENGTH

If the drag coefficient in figure 16 is assumed to be that for a solid flat plate, approximately 1.0, then the critical velocity is predicted to be between 20 and 23 knots, depending on which moment arm is selected. At the other extreme, a drag coefficient of 0.25, the predicted critical velocity is 40 to 45 knots. The critical velocities for a drag coefficent of 0.5, probably the most realistic value, vary from 28 to 31 knots. One must keep in mind that the applied velocity in this case is a uniform velocity over the whole projected surface area.

The final analysis task for both reported mishaps was to estimate S-76 peak profile velocities at mid gross weight for both 0 and 9 knot winds. These peak velocities were estimated at 40 and 70 feet from the center of the rotor for the first and second mishaps, respectively. These results are presented in table 4.

TABLE 4 ESTIMATED SIKORSKY S-76 PEAK ROTORWASH VELOCITIES AT 1.0 AND 3.5 FEET AGL

S-76 Gross Weight = 8000 lb

DISTANCE FROM ROTOR, ft	AMBIENT WIND VELOCITY, kts	HEIGHT ABOVE GROUND, ft	PEAK ROTORWASH VELOCITY, ft
40	0	1.0	50
		3.5	31
40	9	1.0	67
		3.5	47
70	0	1.0	38
		3.5	32
70	9	1.0	54
		3.5	48

If the results in table 4 are compared to the calculated critical overturning moment velocities in figure 16, an evaluation of the two reported mishaps can be made. The reported position of the unknown type of motorcycle in the first mishap was 40 feet from the S-76. Calculated critical overturning moment velocities (figure 16) are considerably exceeded by the estimated rotorwash velocities (table 4) for all motorcycle drag coefficients equal to and greater than the 0.5 value. The required critical overturning velocity may even be exceeded in a 0 knot wind

hover with the flat plate drag coefficient (approximately 1.0). This result leads to one of three possible conclusions: either the analysis methodology or input data are incorrect; the motorcycle characteristics are much different than the measured Harley-Davidson characteristics; or the motorcycle was parked in a different way than the methodology assumes. If the motorcycle is a Harley-Davidson with the wheel pointed toward the kickstand, the overturning moment would be considerably higher. Also, if the motorcycle was parked at an angle to the rotorwash flow, the projected side surface area might be considerably reduced. Of course, it is always possible that the S-76 was farther away than 40 feet when the motorcycle toppled.

The reported separation distance in the second accident, which involved the Harley-Davidson, was 70 to 75 feet. The critical overturning velocity for a drag coefficient of 0.5 (28 to 31 knots) is just slightly exceeded by the calculated S-76 peak velocities for a 0 knot wind condition (32 to 38 knots). With the wind at 9 knots, the estimated S-76 velocities (48 to 54 knots) just slightly exceed the critical values required for the lowest evaluated drag coefficient (40 to 45 knots). Even though correlation is much improved for this mishap, the conclusions discussed in the previous paragraph are equally applicable to this particular scenario.

3.4.3 Conclusions from an Analysis of Mishaps Involving Ground Vehicles

Several conclusions can be reached from the analysis of mishaps involving rotorcraft and ground vehicles. First, there are clear implications that low altitude overflights of parking areas are always risky. Even if rocks and sand are not a hazard to paint, the probability that damage will occur to camper shells, hatchback sunscreens, and motorcycles is significant. Unfortunately, threshold overturning velocities for motorcycles could not be conclusively determined in this analysis. More research will have to be devoted to this subject. However, indications do exist which point to the critical velocity being in the range of 30 to 40 knots. Recommendations from this analysis might be as follows:

1. motorcycle parking areas should always be located as far away from rotorcraft approach paths and landing areas as possible,

2. signs directing camper shell equipped vehicles should be posted to caution owners to park away from approach and landing areas, and

3. automobiles should be provided general warnings that rotorcraft may overfly parking areas, causing sand, dirt, and debris to be blown about at high velocities. Any warnings should emphasize that all doors, windows, sunroofs, sunscreens, etc. be secured.

3.5 PERSONNEL INJURY

Two mishaps involving injury to personnel were reviewed for this report. The information contained in both of the mishap summaries was not sufficiently detailed for a thorough analysis. However, both of these mishaps are excellent examples of incidences which could have easily been avoided. It is hoped that a review of these mishaps will accomplish two goals. The first goal is to help make the reader more aware of the dangers present in these types of mishaps. The second goal is to provide background information for guidelines which may be developed in the future to prevent similiar mishaps from occurring.

The first injury mishap involved a non-standard approach to a hospital helipad. A Sikorsky H-3 class air-sea rescue helicopter arrived at the hospital, and the pilots determined that a non-standard approach would allow them to avoid flying near several emergency vehicles. During the approach, the helicopter flew over a residential house or commercial building close by the hospital. The rotorwash generated during the overflight blew tree limbs, roofing material, and parts of a rooftop ventilator off the roof. Two people working on the roof were injured. In the second mishap, a Sikorsky UH-60 made an approach over a parking lot and guardhouse at an air base in the western United States. The landing approach was flown at approximately 15 knots airspeed at an altitude of approximately 75 feet AGL (as it passed over the parking lot location). This approach was not noticed by the guard until rocks and sand started to impact the guardhouse and nearby automobiles. As the guard hurried to avoid being hit by the rocks and broken window glass, the guard slipped. The guard's leg was broken in the subsequent fall. Physical damage to the guardhouse and nearby automobiles was approximately $1,800. Takeoffs and approaches over this part of the base are now prohibited unless they involve an emergency.

In both of these accidents several lessons can be learned. The first lesson is that non-standard approaches can be dangerous. This is especially true if the final segment of the approach path is above personnel or property that is easily damaged or moved (i.e., automobiles, motorcycles, construction materials). Exposed personnel in these instances cannot be expected to be completely

responsible for their own safety, especially when they have not been told that they are under a potential approach path. Likewise, while pilots do have a responsibility to survey approach pathways for hazardous situations, they will never be able to identify every potential problem from the air. Therefore, careful planning must be used in the design of approach and departure paths to minimize situations where rotorwash may be a hazard.

The second lesson to be learned is that precautions should be taken to eliminate the need for non-standard takeoffs and approaches. This may mean development of alternative approach paths that are rarely used. Also, procedures should be developed to insure standard approach paths are kept clear as intended. An example of this type of problem is discussed in the next section.

3.6 DAMAGE TO LIGHT STRUCTURES

Several mishaps and an operator survey, contained in reference 20, were reviewed for details involving rotorwash damage to light structures. Responses reported in the survey indicate that most structurally-related incidents appear to involve minor roof damage or rotorwash-blown exhaust fumes entering rooftop circulation vents (no specific mishaps were described in the survey). One of the documented mishaps available for review, involving broken windows, was discussed in the previous section since a personnel injury occurred. Two other mishaps, both involving tents, are discussed in the following paragraphs. These mishaps, similiar to the mishaps involving personnel injury, provide examples of mishaps which could have been avoided.

The first of the tent-related mishaps involved a large military Sikorsky CH-54A. Winds were reported to be only 3 knots. The helicopter picked up a 6,000 pound load and departed the area. As the helicopter passed through 50 feet AGL, the flight engineer observed 1 tent in a group of tents 300 feet away become airborne. This tent struck other tents and significant damage was later reported. The report also indicated that the tent may not have been tied down properly. No personnel injuries were reported; however, little doubt exists that they could have occurred. A simple analysis indicates the the peak rotorwash generated velocities at this distance were probably no greater than 25 to 30 knots.

The second reported mishap involved a much smaller helicopter, a Bell 206L. Mathematical modeling of this particular mishap was not possible because of the unknown dynamics involved and today's technology limitations. However, very important lessons can be learned from this particular incident. The helicopter was making a standard

approach to a marked helipad, and winds were less than 15 miles per hour. As the helicopter passed over the 8 to 10 foot high fence which surrounds the helipad area, a tent was blown down and totally destroyed. The skid height of the 206L as it passed over the fence was 50 to 60 feet, and the pilot was adding power to arrest the helicopter's rate-of-descent. The tent was located just outside the fence in an RV park. Large warning signs were posted on the fence. Yet, on numerous occasions towels and other objects were observed drying on the fence. Fortunately, no people were injured in this mishap. The most disturbing aspect of this mishap is that it was noted in the summary that this occurs each year at this site.

Several lessons can be learned from these two incidents. One lesson is that tents are very susceptible to rotorwash. In the first mishap, the collapse was at 100 yards with only a 3 knot ambient wind. The critical threshold velocity in this mishap appears to be approximately 30 knots. In the second mishap, the most alarming fact is that a clearly hazardous scenario is being allowed to continue on a permanent basis. Even though signs clearly warn campers of helicopter operations and potential hazards, the lack of respect for these warnings has created a high probability that a serious injury will occur eventually. A second alarming aspect of this mishap becomes apparent if the long list of mishaps involving objects blown about by rotorwash is reviewed in reference 8. A study of this list clearly would seem to indicate that the RV park is a serious potential hazard to the overflying rotorcraft. Therefore, the development of guidelines controlling the establishment of camping sites and the use of tents in close proximity to public use heliports and vertiports should be a goal for the future. This may require zoning ordinances to prevent certain types of development immediately beyond fenced-off approach and departure zones.

4.0 CONCLUSIONS

The three conclusions presented below are based on a review and in-depth analysis of helicopter rotorwash related mishaps which occurred in typical operational scenarios. The studied mishaps involved helicopter door, cowling, rotor blade, and tailboom damage; the overturning of light fixed-wing aircraft; incidents with oil drums; damage to ground vehicles; personnel injury; and damage to light structures.

4.1 MISHAP DATA REPORTING PROBLEMS

The most significant problem encountered in virtually all of the analyzed mishaps was a lack of documented quantitative facts. Less than 10 percent of the mishaps had any documentation on the ambient wind conditions at the time the mishap occurred. The percentage of reported mishaps containing sketches of mishap geometry was even lower. This lack of information resulted in many assumptions being made in the analysis process. The effect of these assumptions is unknown, but they must certainly be considered significant. It is hoped that improvements can be made in the reporting process in the future to alleviate some of the discussed problems.

4.2 MATHEMATICAL MODELING OBSERVATIONS

It was discovered in the analysis effort that even though quantitative facts were almost non-existent in a majority of the mishap summaries, simple mathematical models appeared to provide quite believable results. These results were validated, wherever possible, with flight test or experimental data from a controlled environment. These results provide hope that with further work, mathematical models should be capable of aiding in the development of separation guidelines for rotorcraft. Models should also be useful in the design of vertiports and heliports.

4.3 THE 30 TO 40 KNOT VELOCITY THRESHOLD

The most useful piece of data to come out of this study is a strengthened substantiation of the 30 to 40 knot peak velocity threshold concept. This concept simply implies that the majority of rotorwash mishaps can be avoided if separation distances are maintained so that impacting rotorwash-generated velocities do not exceed 30 to 40 knots. This concept is by no means yet proven; however, the majority of the results presented to date support it. Implementation of separation guidelines based on this concept may be economically unfeasible in some situations. Clearly, further research is needed to conclusively validate any effects of this concept on safety or economic factors.

5.0 RECOMMENDATIONS

Three recommendations result from this analysis effort. Successful implementation of these recommendations will dramatically improve the engineering community's ability to develop separation guidelines for all types of rotorcraft which are realistic, justifiable (scientifically and economically), and most importantly, safe.

5.1 ADDITIONAL MISHAP DATA AND MODELING

The acquisition of additional mishap data would significantly aid the process of developing rotorcraft separation guidelines. It is recommended that these data be acquired from two sources. The first is the U.S. Navy Safety Center. Numerous mishaps related to rotorwash are on file with this organization. The data should be obtainable by the Federal Aviation Administration through some form of interagency agreement. The second source of data should be obtained through experimental research. A flight test program should be conducted to measure threshold rotorwash velocity values which will overturn personnel, oil drums, and motorcycles, as well as produce damage to rotorcraft doors, cowlings, and rotor blades. An experiment measuring the velocity flowfield around a small structure should also be conducted. These types of experiments can be conducted without actually damaging the tested equipment. Aircraft confiscated by U.S. law enforcement agencies would be good candidates for this type of testing. After completion of the data acquisition tasks, mathematical models for these types of mishaps should be upgraded, validated, and documented.

5.2 WIND AND LOW SPEED MANEUVERING EXPERIMENTS

Rotorwash flight test data documenting the effects of both wind and maneuvering near hover should be acquired as soon as possible. The effect of a constant ambient wind significantly increases the potential for rotorwash-related accidents (up to some as yet undetermined windspeed). Three common rotorcraft maneuvers also have the potential to generate higher rotorwash velocities than are measured in a stabilized hover on a calm day. These three maneuvers are the initial acceleration maneuver by a rotorcraft from hover during takeoff, the final decelerating flare to a hover during landing, and air taxiing. Following acquisition of these flight test data, rotorwash analysis models should be upgraded to simulate these effects, validated against the flight test data, and documented. Until this recommendation is implemented, questions will continue to exist with respect to the definition of worst case scenarios in all rotorwash safety analyses.

5.3 COORDINATED INTERAGENCY SAFETY STUDY

A coordinated effort should be proposed between the Federal Aviation Administration, the National Transportation Safety Board, and U.S. Army/Navy Aviation Safety Centers to collect very detailed rotorwash mishap information over a fixed period of time, i.e. three years. Forms for information collection would be developed by the FAA and approved as being practical for use by the three safety agencies. Data obtained during the fixed period of time would be analyzed by the FAA to develop a better understanding of rotorwash related mishaps, correlate and improve predictive mathematical models, and develop and justify rotorcraft separation criteria as required. All data, mathematical models, and other results would be documented and made available for use by all of the participating agencies at the conclusion of the data collection period. A similiar recommendation has been proposed in reference 7.

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